

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**FLEET PLANNING AND NETWORK
OPTIMIZATION IN SUPPLY CHAINS UNDER
UNCERTAIN ENVIRONMENTS**



by
Kemal SUBULAN

July, 2016
İZMİR

FLEET PLANNING AND NETWORK OPTIMIZATION IN SUPPLY CHAINS UNDER UNCERTAIN ENVIRONMENTS

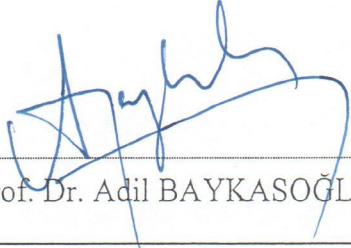
**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University In
Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy
in Industrial Engineering, Industrial Engineering Program**

**by
Kemal SUBULAN**

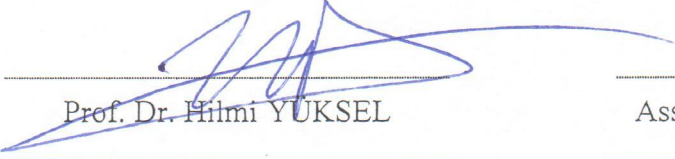
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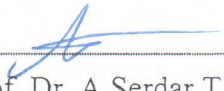
We have read the thesis entitled “FLEET PLANNING AND NETWORK OPTIMIZATION IN SUPPLY CHAINS UNDER UNCERTAIN ENVIRONMENTS” completed by KEMAL SUBULAN under supervision of PROF. DR. ADİL BAYKASOĞLU and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.


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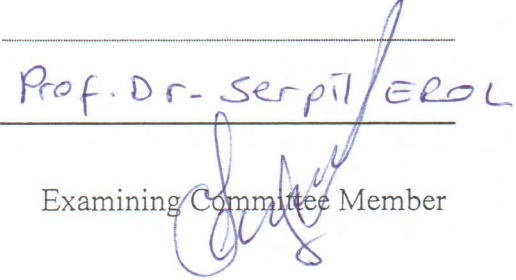
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FLEET PLANNING AND NETWORK OPTIMIZATION IN SUPPLY CHAINS UNDER UNCERTAIN ENVIRONMENTS

ABSTRACT

This thesis deals with network optimization in supply chains under fully uncertain environments and fleet planning problems in intermodal transportation networks. Firstly, a novel transformation method and a direct solution approach based on constrained fuzzy arithmetic concept are developed for solving fully fuzzy transportation and transshipment problems where all of the model parameters and decision variables are stated as fuzzy numbers. In contrast to the linear programming based transformation method, a fuzzy decoding procedure is also applied within a metaheuristic algorithm in order to solve the problems directly. Then, a parametric solution method is also proposed to solve fully fuzzy reverse logistics network design problems without using constrained fuzzy arithmetic concept. All of these developed solution methodologies are also able to consider decision maker's attitude toward risk while generating fuzzy efficient solutions under various uncertainty levels. Afterwards, a new scenario based stochastic and possibilistic programming model is formulated for a multi-objective lead-acid battery closed-loop supply chain network design problem by managing both of the financial and collection coverage risks. Finally, a decision support system based on a fuzzy-stochastic mathematical model is developed for a real-life intermodal load and fleet planning problems of an international logistics company in Turkey. The proposed decision support system integrates various levels of decisions associated with several decision makers. In fact, multi-mode load planning, fleet sizing-composition, fleet allocation, fleet inventory control, fleet expansion-reduction and empty vehicle repositioning problems are incorporated within the proposed model. The extensive computational results have shown that effective and efficient load and fleet plans can be provided by making use of the proposed model in terms of the conflicting sustainability objectives such as total transport cost, transit time and environmental issues.

Keywords: Fully fuzzy mathematical programming, constrained fuzzy arithmetic, risk management in closed-loop supply chains, intermodal transportation, fleet planning

TEDARİK ZİNCİRLERİNDE BELİRSİZLİK ALTINDA FİLO PLANLAMA VE AĞ OPTİMİZASYONU

ÖZ

Bu tez kapsamında, tam belirsizlik koşulları altında tedarik zinciri ağ optimizasyonu ve intermodal ulaştırma sistemlerinde filo planlama problemleri çalışılmıştır. Öncelikle, tüm model parametreleri ve karar değişkenleri tamamen bulanık ulaştırma problemlerinin çözümü için sınırlandırılmış bulanık aritmetik temelli bir dönüştürme yöntemi ve direkt çözüm yaklaşımı geliştirilmiştir. Geliştirilen doğrusal programlama tabanlı dönüştürme yönteminden farklı olarak, söz konusu problemlerin doğrudan çözümü için metasezgisel temelli bulanık çözümleme algoritması da önerilmiştir. Bu çalışmalara ek olarak, tamamen bulanık tersine lojistik ağ tasarım problemlerinin çözümüne yönelik sınırlandırılmış bulanık aritmetik kullanılmadan parametrik bir çözüm yöntemi de geliştirilmiştir. Önerilen bütün çözüm yöntemlerinde, farklı belirsizlik düzeylerinde bulanık etkin çözümler üretilirken, karar vericinin riske karşı duyarlılığı da dikkate alınabilmektedir. Daha sonra, finansal ve toplama risklerinin birlikte yönetildiği, çok amaçlı bir akü kapalı çevrim tedarik zinciri ağ tasarımı için senaryo tabanlı rassal-bulanık optimizasyon modeli geliştirilmiştir. Son olarak, Türkiye’de faaliyet gösteren uluslararası bir lojistik işletmesinin çok modlu yük ve filo planlama problemlerinin çözümü için rassal-bulanık matematiksel programlama tabanlı bir karar destek sistemi geliştirilmiştir. Geliştirilen karar destek sistemi ile birçok karar vericinin farklı seviyelerdeki karar problemlerine entegre bir şekilde çözümler üretilmektedir. Bir başka ifadeyle, çok modlu yük planlama, filo büyüklüğü-kompozisyonu belirleme, filo atama, filo stok kontrolü, filo genişletme-daraltma ve boş araç yeniden konumlandırma problemleri geliştirilen modelde eş zamanlı olarak ele alınabilmektedir. Gerçekleştirilen detaylı hesaplamalı analizler göstermektedir ki önerilen karar destek sistemi yardımıyla toplam taşımacılık maliyeti, toplam teslimat süresi ve çevresel kriterler gibi çelişkili sürdürülebilirlik hedefleri doğrultusunda etkin ve etkili yük ve filo planları oluşturulabilmektedir.

Anahtar kelimeler: Tamamen bulanık matematiksel programlama, sınırlandırılmış bulanık aritmetik, kapalı çevrim tedarik zincirlerinde risk yönetimi, intermodal taşımacılık, filo planlama

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CHAPTER ONE

INTRODUCTION

1.1 Background and Research Motivations

In the recent fuzzy mathematical programming literature, fully fuzzy linear programming which incorporates fuzzy decision variables has become a hot research topic. On the other hand, there is a lack of studies in the current literature which focused on fuzzy solution of mathematical programs under fully uncertain environments. Unfortunately, most of these available studies are based on extension principle of fuzzy set theory or standard fuzzy arithmetic operations which may lead to impractical and unrealizable solutions for many real-life engineering optimization problems. In detail, classical fuzzy arithmetic may cause information-deficient results and overestimation in fuzzy solutions. Moreover, risk attitude of the decision makers are not taken into account by the existing methods while generating fuzzy efficient solutions. Most of the present methods cannot handle the intersections between different fuzzy membership functions in modeling the fuzzy mathematical programs. Thus, they may offer only infeasible solutions. Fortunately, these intersections can be considered appropriately through the requisite constraints in fuzzy arithmetic. To overcome these drawbacks, constrained fuzzy arithmetic (CFA) based solution approaches are required. Furthermore, the majority of current methods are transformation methods which convert the fuzzy mathematical program into the crisp equivalent form and then solve it by a traditional optimization technique. These indirect solution methods may cause information losses, less flexibility and higher computational effort since increasing number of variables and constraints during the transformation process. For this reason, development of direct solution methods is needed to solve fully fuzzy linear programming problems.

Before managing the risks in supply chains (SCs), the uncertainties embedded in the stated problem should be handled successfully since the primary sources of risks are these uncertainties. In addition, many supply chains, closed-loop supply chain (CLSC) planning problems may contain different uncertainty types such as stochasticity, fuzziness, dynamism etc. simultaneously. However, most of the studies in the literature cope with these uncertainty types independently. For these reasons,

integrated approaches should be developed for solving fuzzy and stochastic SC optimization models. Apart from the classical risk management models in which just financial risks of SCs are considered, demand coverage and collection coverage risks should also be taken into account while designing and planning the SCs and CLSCs. The classical risk management measures are generally valid for crisp environments. Therefore, fuzzy or stochastic versions of the available risk metrics with crisp targets should be proposed in order to handle some ambiguities in a more effective manner.

For the last decade, there has been an increasing interest in modelling and solving load planning and fleet planning problems in intermodal transportation systems. These issues are much more complicated than the unimodal transportation planning problems because of concerning with several complex decisions concurrently, i.e., transportation mode and service type selection, outsourcing, fleet sizing/composition, fleet allocation, fleet expansion/reduction, empty vehicle repositioning, fleet inventory control etc. However, these problems are generally modelled and solved by the existing studies in a separated way. Unfortunately, simultaneous flows of import and export freights among the different locations on the logistics network are considered by only limited researches. Again, consolidation or exchange of freights at the transshipment nodes are not generally taken into consideration by the existing papers. Besides, a few investigations are available in the literature which incorporate various decision levels (strategic, tactical and operational) of different decision makers (drayage, terminal, finance and intermodal operators etc.). Moreover, there is still scarcity of extensive mathematical programming models, Operations Research (OR) and Artificial Intelligence (AI) based solution approaches in the literature for multimodal transportation systems. As a final point, in addition to minimize the transport cost and profit orientations, multi-objective optimization models that also consider sustainability issues should be developed for intermodal load and fleet planning problems. Hence, there is a critical need to develop decision support systems based on advanced mathematical programming models for intermodal fleet management under uncertainty. Similar with an ERP software, this decision support system should have various modules such as load planning, fleet optimization, loaded/empty truck positions etc. which support different interactive decision makers in strategic, tactical and operational decision making processes.

1.2 Research Objectives, Methodologies and Framework of the Thesis

The overall objective of this thesis is to model and solve fleet planning and transportation network optimization problems in supply chains under fully uncertain environments. There are also five crucial objectives of this thesis because of focusing on different research studies.

Research objective 1: *Developing novel direct/indirect solution methods based on CFA concept for modelling and solving fully fuzzy balanced/unbalanced transportation and transshipment problems by considering decision maker's attitude toward risk. Presenting more reliable, applicable and information-efficient fuzzy optimal solutions for risk-averse decision makers.*

Research objective 2: *Solving a generic RL network design problem by an improved decoding procedure and seeker optimization algorithm. Developing a new parametric approach for fuzzy version of the problem including fuzzy decision variables. Comparison of the proposed approach with the well-known methods in the literature.*

Research objective 3: *Modelling and solving a hybrid stochastic and possibilistic CLSC network design problem in a lead/acid battery industry. Adapting different risk measures in order to manage financial and collection coverage risks simultaneously.*

Research objective 4: *Formulating a mixed-integer programming model for multi-objective, multi-mode and multi-period load planning problem with simultaneous import/export freight flows by considering sustainability issues.*

Research objective 5: *Developing a decision support system based on a novel fuzzy and stochastic mathematical program for strategic, tactical and operational fleet planning problems in intermodal transportation networks. Integrating the fleet sizing/composition, fleet allocation, fleet expansion/reduction, fleet inventory control, and empty vehicle repositioning problems into a single optimization model. Providing various compromise fleet plans to EKOL Logistics Inc. by taking into account several conflicting objectives and constraints under uncertainty.*

Finally, the research framework of this PhD thesis can be summarized as in Table 1.1 by incorporating some problem characteristics, used solution methodologies etc.

Table 1.1 Summary of the research objectives, solution methodologies and framework of this thesis

Chapters	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6
Network	- Classical single stage transportation network - Two-stage transshipment network	Multi-stage reverse logistics network	Multi-stage closed-loop supply chain network	Intermodal transportation network	Intermodal transportation network
Problem Definition	Fully fuzzy transportation and transshipment problems with fuzzy decision variables	Fully fuzzified reverse logistics network design problem	Multi-objective lead/acid battery closed loop supply chain network design problem	Multi-mode load planning or intermodal freight transportation planning problem	Intermodal fleet planning problem with several sub-problems fleet sizing/composition, fleet allocation, empty vehicle repositioning, fleet expansion/reduction etc.
Solution Methodologies	- CFA based transformation method with fuzzy linear programming - CFA based decoding procedure with PSO algorithm	- Swarm intelligence techniques (SOA & PSO) for deterministic problem - Parametric fuzzy optimization method based on SFA and α-cuts	- Mixed-integer linear programming - Scenario-based stochastic optimization - Fuzzy mathematical programming - Different risk management measures (variability index, downside risk, conditional value at risk etc.)	- Mathematical modelling - Compromise programming with many distance metrics - Fuzzy goal programming with different importance and priorities, - Weighted additive fuzzy goal programming - Interactive fuzzy goal programming	- Mathematical programming based decision support system - Chance-constrained stochastic optimization method - A resolution method for fuzzy linear programming - Fuzzy multi-objective optimization with weighted additive fuzzy goal programming
Fuzzy Components	- Fuzzy transport capacities - Fuzzy demands - Fuzzy transport costs - Fuzzy transportation quantities	- Amounts of returned products - Disposal fraction - Weight of the product - Material contribution - Recovery rate - Fixed opening costs - Transportation costs - Collection, recovery, disposal and warehousing capacities - All of the transportation decisions	- Fixed opening costs - Production, transportation recycling, collection, purchasing, disposal costs and selling prices - Recycling rate - Maximum allowable distances for demand and collection coverage - Upper bounds on number of opened facilities	Aspiration levels of the goals	- All of the cost terms: marine, road and railway transport costs - Marine, rail and road transit times - Number of working days in each month at the order countries - Truck and trailer availabilities - Transport capacities of Ro-Ro vessels - Maximum number of marine cruises - Lower bounds on utilization rates of Ro-Ro vessels - Lower and upper bounds on block train services
Stochastic parameters	N.A	N.A	- Demand of battery dealers - Returned fraction - Disposal rate	N.A	The monthly import and export freight demands of order countries
Objective Functions	Minimize total fuzzy transportation and transshipment costs	Minimize the overall cost of reverse logistics system	- Minimize expected CLSC costs - Maximize total expected collection coverage - Minimize the financial and collection risks	- Minimize overall transport costs - Minimize total transit time or maximize customer satisfaction - Minimize total CO₂ emission value	- Minimize overall transport costs - Minimize total transit time or maximize customer satisfaction - Minimize total CO₂ emission value

1.3 Outline of the Thesis

The rest of this thesis includes six chapters. This first chapter is devoted to presentation of the introduction, research motivations and goals. Each chapter contains a relevant literature review on fuzzy transportation problem, fully fuzzy linear programming problems, risk management in supply chains, intermodal freight transportation planning problem, fleet sizing and composition problems etc. The remaining chapters of this thesis can be organized as follows.

In Chapter 2, CFA based solution methodologies are presented for both direct and indirect solution of fully fuzzified transportation and transshipment problems where all of the model parameters and decision variables are stated as uncertain. In Chapter 3, analysis of fully fuzzy linear programming models with fuzzy decision variables is performed over a reverse logistics network design problem. Seeker optimizer algorithm is used to solve crisp form of the problem. Then, a parametric approach is also developed for solution of fuzzy version of the problem without CFA concept.

In Chapter 4, a hybrid multi-scenario based stochastic and possibilistic programming model is developed for a multi-objective, multi-echelon lead/acid battery CLSC network design problem. Later, different risk management metrics are implemented to minimize both of the financial and collection coverage risks.

In Chapter 5, a mixed-integer programming model is formulated for a sustainable intermodal transportation planning problem of an international logistics company in Turkey. Then, different fuzzy multi-objective optimization techniques are applied to obtain compromise load plans under cost, time and environmental objectives.

In Chapter 6, a decision support system depending upon a fuzzy and stochastic mathematical programming model is developed for an integrated strategic, tactical and operational intermodal fleet planning problem. The proposed fleet management system covers various sub-problems such as fleet sizing/composition, load planning, empty vehicle repositioning, fleet expansion/reduction etc. simultaneously.

Chapter 7 presented a brief summary, concluding remarks, original contributions of the thesis and future research directions.

1.4 Produced Publications Based on the Researches in the Scope of This Thesis

The following scientific research papers has been generated during the preparation of this thesis which aims at solving transportation network optimization and fleet planning problems in supply chains under uncertain environments. These papers are either published or under review status for journal publication. Thesis chapters incorporates the following papers which are assigned to the specific sections.

Chapter 2, Section 2.5:

- Baykasoğlu A. & Subulan K. (2016). A novel constrained fuzzy arithmetic based method for fully fuzzy transportation problems with decision maker's attitude toward risk, (Submitted to an international Journal).

Chapter 2, Section 2.6:

- Baykasoğlu A. & Subulan K. (2016). A Direct Solution Approach Based on Constrained Fuzzy Arithmetic and Metaheuristics for Fully Fuzzy Transportation Problems, (Submitted to an international Journal).

Chapter 3, Section 3.4:

- Subulan, K., Baykasoğlu, A. & Saltabaş, A. (2014). An improved decoding procedure and seeker optimization algorithm for reverse logistics network design problem. *Journal of Intelligent & Fuzzy Systems*, 27(6), 2703-2714.

Chapter 3, Section 3.5:

- Baykasoğlu A. & Subulan K. (2015). An analysis of fully fuzzy linear programming approaches with fuzzy decision variables through logistics network design problem. *Knowledge-Based Systems*, 90, 165-184.

Chapter 4:

- Subulan K., Baykasoğlu A., Özsoydan F.B., Tasan A.S. & Selim H. (2015). A case-oriented approach to a lead/acid battery closed-loop supply chain network design under risk and uncertainty. *Journal of Manufacturing Systems*, 37(1), 340-361.

Chapter 5, Section 5.3:

- Baykasoğlu A. & Subulan K. (2016). A new mathematical programming model for load planning problems in intermodal transportation networks, *Journal of the Faculty of Engineering and Architecture of Gazi University*, 31(2), 381-392.

Chapter 5, Section 5.4:

- Baykasoğlu A. & Subulan K. (2016). A multi-objective sustainable load planning model for intermodal transportation networks with a real-life application, (Under review, revised and submitted to an international Journal).

Chapter 6, Section 6.2:

- Baykasoğlu, A., Dudaklı, N., Subulan, K., Taşan, A.S., Kaplan, M.C. & Turan, M. (2016). İntermodal taşımacılık sistemlerinde filo yönetimi, *Lojistik*, Sayı 36, 28-37.

Chapter 6, Section 6.5.2:

- Baykasoğlu, A., Subulan, K., Dudaklı, N. & Tasan, A.S. (2016). An integrated fleet sizing, allocation and empty vehicle repositioning model in multimodal transportation systems with an application to Turkish logistics industry. (Submitted to an international Journal).

Chapter 6, Section 6.5.5:

- Baykasoğlu, A. & Subulan, K. (2016). A decision support system based on a novel fuzzy and stochastic intermodal fleet planning model with multiple objectives. (Submitted to an international Journal).

CHAPTER TWO

NEW CONSTRAINED FUZZY ARITHMETIC BASED APPROACHES FOR DIRECT & INDIRECT SOLUTION OF FULLY FUZZY TRANSPORTATION AND TRANSSHIPMENT PROBLEMS

2.1 Chapter Introduction

Recently, there is a growing interest by the researchers to model and solve fully fuzzy linear programming (FFLP) and fully fuzzy transportation problems (FFTPs) in which all of the parameters as well as the decision variables are considered as fuzzy numbers. However, there is still a scarcity of solution methodologies on both FFTP and fuzzy mathematical programming models with fuzzy decision variables. In fact, decision variables of a fuzzy mathematical program where all of the parameters are defined as fuzzy numbers should also be considered as fuzzy. Because, the fuzzy aspect of the problem may be partly lost by limiting the decision making process with the crisp solutions. For this reason, obtaining fuzzy efficient solutions instead of crisp solutions in fully uncertain environments which provide ranges of flexibility to decision maker(s) seems more impressive (Dubois & Prade, 1984; Xiaozhong, 1997). In other words, presenting the reasonable range of values for the fuzzy variables can be comparatively better than the currently available crisp solutions (Baykasoğlu & Gocken, 2012). Such a fuzzy solution will also provide possible outcomes with certain degree of memberships to the decision maker(s). This is especially useful for strategic decisions where more uncertainties may exist. Therefore, uncertainties on the parameters should be reflected into the results. This is because fuzzy solutions may serve the regions containing potential satisfactory solutions around the optimal solutions to the decision maker(s). Thus, the final decision step can be performed by the actual decision maker(s) as crisp ones. By taking the decision variables as fuzzy, the choice of the crisp decisions among the fuzzy solutions can also be supported (Baykasoğlu & Gocken, 2012). In detail, it is possible to generate crisp decisions from the fuzzy solutions by making use of any defuzzification method or some other auxiliary methods. Nevertheless, achieving the optimal solutions of FFLP problems is a challenging task. Because, there is no algorithm which determines the exact values of the optimal fuzzy decision variables (Buckley & Feuring, 2000).

Most of the solution approaches for transportation problems considered uncertainty of only the parameter values, i.e., demands of the destinations, capacities of the sources and transportation costs etc. However, decisions on the transportation quantities can also be considered as fuzzy numbers. It was also highlighted by Giri et al. (2015) that when the source capacities, demands and transportation costs are imprecise, the transportation quantities automatically demand to be imprecise since the sum of the transportation quantities satisfy the fuzzy source availabilities and fuzzy demands in equality or inequality sense. Therefore, fully fuzzy solution is better than the crisp one for this kind of transportation problems with fully uncertainty in terms of the maximal fulfillment of demand. According to Chandran and Kandaswamy (2012), more flexibility can be presented to the decision maker when the objective value and transportation allocations are represented by fuzzy numbers. At the end, in order to obtain a feasible shipping plan, the decision maker may defuzzify the fuzzy transportation amounts.

In the literature, most of the previous methods (Klir, 1997; Liu & Kao, 2004; Lotfi et al., 2009; Pandian & Natarajan, 2010; Kumar & Kaur, 2011; Kumar et al., 2011; Kaur & Kumar, 2011; Gupta et al., 2012; Ezzati et al., 2015) for solving FFLP problems and FFTPs utilize Zadeh's (1975) extension principle which is one of the most important and powerful tools in fuzzy set theory. However, the usage of standard fuzzy arithmetic may lead to impractical and inapplicable solutions for many real-world problems due to not taking into account the additional information available in the real-life applications. It was also emphasized by Klir (1997) that direct application of standard fuzzy arithmetic to the problems in various applications may cause questionable results as also noted by Yager (1980), Sanchez (1984), Dong and Wong (1987) and Buckley (1992). Indeed, the existing methods may also produce risky and unrealizable solutions for many real-world problems. For a practical fuzzy transportation problem, risky situations may arise for capacity availability of sources and demand satisfactory of destinations while realizing the transportation operations. For instance, source capacities may become insufficient due to the negative elements of fuzzy remaining capacities and demands may not be fully satisfied due to the positive elements of fuzzy remaining demands. These correspond to the capacity unavailability and demand unsatisfactory risks. Moreover, solutions provided by these

methods may not appropriate for the risk-averse decision maker(s). In other words, the standard fuzzy arithmetic may cause information-deficient results and/or overestimation in the solutions since ignoring the known constraints in fuzzy arithmetic (Klir & Cooper, 1996; Klir & Pan, 1998). Thus, the applicability of standard fuzzy arithmetic is limited for some engineering problems. As mentioned by several researchers, almost none of the practical applications are constraint-free (Klir, 1997). Thus, constrained fuzzy arithmetic (CFA) can be considered more important concept than the standard fuzzy arithmetic in terms of providing more reliable solutions for many practical applications (Klir & Cooper, 1996; Klir, 1997; Klir & Pan, 1998).

In this chapter, solution of FFTP and transshipment problems with fuzzy decision variables is presented. In detail, all of the parameters and decision variables of a balanced and/or unbalanced transportation problems are defined as triangular fuzzy numbers. Then, new approaches which are based on CFA concept is proposed for direct and indirect solution of FFTP. The proposed approaches are also able to take into account decision maker's attitude toward risk. Actually, a new CFA based transformation method is first developed for modeling and solving FFTP. In this proposed indirect solution approach, the requisite crisp and/or fuzzy constraints between the base variables of triangular fuzzy numbers are provided from the decision maker. Thereafter, fuzzy arithmetic operations are performed by taking into account these additional information while transforming the FFTP into crisp equivalent form. Therefore, risk-free and more reliable solutions can be provided according to decision maker's risk attitude.

However, the majority of existing solution methodologies in the literature for fuzzy transportation problems is transformation methods (as our firstly developed CFA based transformation approach) in which the fuzzy mathematical program is first converted into its crisp equivalent form and then solved by a classical optimization technique (Baykasoğlu & Gocken, 2012). In other words, these methods transform the fuzzy transportation problem into a set of crisp linear programs and generally utilize optimization techniques for linear programming to obtain a solution. As mentioned previously, these methods are indirect solution techniques and may cause loss of information during the transformation process. Furthermore, the model size (number

of constraints and decision variables) may generally increase due to the transformation process. Therefore, the required computational effort will also increase in the solution phase. Based on these motivations, this chapter also presents a direct solution approach based on CFA concept and Particle Swarm Optimization (PSO) algorithm for solving FFTP. In detail, the secondly proposed direct solution approach integrates PSO algorithm with priority-based encoding and a fuzzy decoding procedure based on CFA concept. The proposed decoding procedure makes use of CFA operations, a defuzzification technique and α -cuts. The defuzzification technique is used into the proposed decoding procedure so as to rank the fitness function values and comparison of the fuzzy transportation cost parameters. In order to generate new solution vectors and to obtain fuzzy efficient solutions, this decoding procedure is incorporated into a PSO algorithm. Conversely, any other metaheuristic algorithm can also be utilized instead of PSO. By using such a direct solution approach, one can eliminate both of the usage of standard fuzzy arithmetic operations and conversion of a fuzzy mathematical program into its classical crisp equivalent form. Apart from the available literature, while realizing the priority-based PSO algorithm, unbalanced fully fuzzy transportation cases are decoded without adding any dummy nodes. This improvement yields more efficient and effective way of encoding/decoding procedures and also computational efficiency. Moreover, “*equal fuzzy transportation cost*” or “*equal defuzzified transportation cost*” issues are also taken into account for better reflection of the real-life transportation applications.

Both of the proposed approaches are also based on α -cuts (alpha-parametric approaches) so it is possible to consider/model risk tolerances and various uncertainty levels. Additionally, in contrast to the most of previous existing methods which cannot handle intersections between different fuzzy membership functions in modeling the fuzzy mathematical programs (i.e., they provide only infeasible solution), the proposed approaches are able to consider intersections effectively by making use of the requisite constraints in CFA. The proposed approaches are also applicable to both symmetric and non-symmetric triangular fuzzy numbers. To the best of our knowledge, the developed approaches are the first one which applies CFA concept to transform or directly solve fuzzy transportation problems.

In order to show validity and practicality of the proposed approaches, different types of balanced/unbalanced fuzzy transportation problems are generated and provided solutions are also compared with other methods available in the literature. In contrast to the compared methods, the proposed approaches maintain information efficient and applicable results since taking into account the supplementary information represented by the requisite constraints. In fact, computational results obtained from the proposed approaches have shown that relatively more precise solutions can be provided to “*risk-averse*” and “*partially risk-averse*” decision maker(s). The proposed approaches can also successfully provide fuzzy efficient solutions for “*risk seekers*” with high degree of uncertainty similar to the other existing methods. In detail, most of the cases, the solutions found by the existing methods constitute the bounds of the fuzzy efficient solutions provided by our proposed CFA based approaches.

This chapter is organized as follows. A brief literature review on fully fuzzy transportation problems with and without fuzzy decision variables is presented in Section 2.2. Basic definitions and fundamental notation related to CFA concept are introduced in Section 2.3. In addition to problem description and mathematical formulation of a fully fuzzy transportation problem, general properties of different types of FFTP are also given in Section 2.4. Section 2.5 presents foundations and basic principles of proposed CFA based indirect solution approach or transformation method under both crisp and fuzzy relations/inequalities. In Section 2.6, CFA based decoding procedure with a metaheuristic application is presented for direct solution of balanced and unbalanced FFTP. In Section 2.7, some numerical examples on various types of FFTP are provided and the results are compared with the current methods in the literature. Finally, conclusions, discussions and future research directions are given in Section 2.8.

2.2 A Brief Literature Review on Fuzzy Transportation Problem

An overview of the articles which studied fuzzy transportation problem and discussed related solution methodologies are summarized for both crisp and fuzzy decision variables as follows:

One of the earliest work on fuzzy transportation problem with fuzzy constraints which involve triangular form of membership functions for supplies and demands was presented by Oheigeartaigh (1982). The relationship among the algebraic structure of the optimum solution of the deterministic transportation problem and its fuzzy equivalent was also examined in that paper. Chanas et al. (1984) proposed parametric programming approach which simultaneously satisfies the imprecise constraints and goal with a maximal degree while solving transportation problems with crisp coefficients and fuzzy constraints. Different kinds of information such as crisp, interval values and fuzzy numbers for the supply and demand levels of a given transportation problem was considered by Chanas et al. (1993). They developed classical, interval and fuzzy mathematical programming models for all of these cases. Then, the links among these models were maintained by emphasizing on the fuzzy transportation problem. An algorithm which provides all of the efficient solutions of a transportation problem with fuzzy cost coefficients was developed by Chanas and Kuchta (1996). In fact, fundamentals of that algorithm mainly depend on transportation simplex method and a modification of Zeleny's algorithm for solving bi-criteria transportation problem which is the converted version of the examined fuzzy transportation problem.

Integer fuzzy transportation problem which involves integral constraints such that every value of fuzzy supply and demand is an integer and the transportation amounts are all integers was solved by Tada and Ishii (1996). They aimed to yield an optimal transportation flow which maximizes the smallest value of all membership functions under an upper limit on the total transportation cost. A parametric approach was utilized by Jimenez and Verdegay (1998) to obtain fuzzy solutions for the fuzzy solid transportation problem in which mode of transport was also included. They also considered the interval solid transportation problem. In their study, vague parameters such as supplies, demands and conveyance capacities were taken as trapezoidal fuzzy numbers. In fact, the fuzzy solutions were provided for the transportation case under fuzzy equality constraints. A fuzzy solution of the solid transportation problem with fuzzy constraints related to the supplies, demands and conveyance capacities was provided by Jimenez and Verdegay (1999) by applying an Evolutionary Algorithm (EA) based solution method. In detail, the auxiliary parametric non-linear program

associated with the fuzzy solid transportation problem was solved by EA-based method and superior approximate parametric solutions were obtained in comparison with the well-known non-linear solution technique namely gradient method.

A fuzzy programming approach based on Zadeh's min operator was utilized by El-Wahed (2001) to find optimal compromise solution of a transportation problem with several objectives. While constructing the membership functions of the objectives, pay off matrix was used to determine lower and upper bounds. The fuzzy optimization model of the compromise problem with linear membership functions was converted into the deterministic equivalent by introducing an auxiliary variable. According to the computational analysis, it has shown that fuzzy programming approach may present superior results when compared to the interactive algorithm in terms of solution quality and required computational effort. A method based on the extension principle was developed by Liu and Kao (2004) in order to calculate the membership functions of the fuzzy total transportation costs for the transportation problems with equality and inequality constraints. In their method, the fuzzy transportation problem was converted into two-level crisp mathematical programs. In addition, the objective values were derived by enumerating different α -values.

A multi-objective transportation problem with fuzzy cost coefficients, fuzzy supply quantities and fuzzy demands was handled by Ammar and Youness (2005). The concepts of fuzzy efficient and α -parametric efficient solution were introduced with the relation among these solutions. Moreover, an algorithm was presented to determine the stability set of the parametric multi-objective non-linear transportation problem. A parametric approach was proposed by Gani and Razak (2006) to solve the two-stage fuzzy cost minimization transportation problem by considering the minimum requirements of destinations in stage-I and surplus quantity left of sources in stage-II. After conversion to α -parametric form of the problem, Vogel's approximation method was applied to get the basic feasible solution. A fuzzy Monte Carlo method was implemented by Buckley et al. (1992) to generate approximate integer solutions to a fuzzy transportation problem in which supplies, demands and unit transportation costs were represented by triangular fuzzy numbers. For the comparison of the triangular

fuzzy numbers, Buckley's ranking method and the minimum transportation cost value was determined sequentially during the simulation run.

A genetic algorithm approach consisting of two phases is proposed by Lin (2009) to solve transportation problem. In the first phase, a fuzzy number which represent the fuzzy demand or supply was simulated by distributing an imprecise value into certain partition points and then GA approach was utilized to evolve the values in each partition point where the final values correspond to the membership degree of that fuzzy number. For the evaluation and selection mechanisms of the GA, signed-distance fuzzy ranking procedure was implemented and thus estimated quantities related to the fuzzy parameters were provided. After that, defuzzified problem instance was solved by GA in the second phase to obtain Pareto optimal solutions to the original fuzzy transportation problem.

An algorithm namely, fuzzy zero point was introduced by Pandian and Natarajan (2010) for finding fuzzy optimal solution of balanced fully fuzzy transportation problem where the uncertain parameters are represented by trapezoidal fuzzy numbers. A method which depends upon classical transportation methods and a fuzzy ranking function was proposed by Kaur and Kumar (2011). Another method which is based on fuzzy linear programming and classical transportation methods was proposed by Kumar and Kaur (2011) for solving balanced fully fuzzy transportation problems. A simplex type algorithm including two phases, i.e., basic variable phase and feasibility phase, was presented by Gani et al. (2011) in order to solve fully fuzzy transportation problem in an effective and efficient way which does not need to use any artificial variable.

The transportation problem with fuzzy equality constraints for the supply and demand points was transformed into the crisp equivalent form by using a parametric fuzzy ranking operator (Basirzadeh, 2011). Then, the crisp transportation problem was solved through the classical transportation algorithms. That method was applicable for the transportation problems with maximization or minimization criterion and also type of the used fuzzy number such as triangular, trapezoidal, *L-R* type, normal or abnormal does not matter. It should also be noted here that optimal solution of the problem can be obtained as either crisp or fuzzy forms.

Another method which was named as Mehar's method was proposed for solving both balanced and unbalanced multiple objective fully fuzzy transportation problems by Gupta et al. (2012). By their proposed method, exact fuzzy optimal solution of a fully fuzzy transportation problem can be provided from the solution of a crisp multi-objective linear program. A direct extension of classical transportation approaches was performed by Kaur and Kumar (2012) for solution of a transportation problem with generalized trapezoidal cost coefficients. In detail, generalized fuzzy north-west corner method, generalized fuzzy least-cost method and generalized fuzzy Vogel's approximation methods were introduced to achieve initial basic feasible solution. Then, generalized fuzzy modified distribution method was applied to get the fuzzy optimal solution. A new algorithm based on score method which ranks the fuzzy numbers was proposed by Chandran and Kandaswamy (2012) for direct solution of fully fuzzy transportation problems including general fuzzy numbers. Their method is applicable for both balanced and unbalanced cases and presents more flexibility to decision makers since the objective and allocations, i.e. transportation amounts are represented by non-negative fuzzy numbers. A new method was developed by Gupta and Kumar (2012) to solve multi-objective balanced transportation problem in which all of the parameters were stated as interval-valued fuzzy numbers. In the transformation process, signed distance ranking function was applied on the interval valued fuzzy numbers and the provided classical multi-objective linear program was solved by fuzzy programming technique in order to find non-dominated solutions. The computational complexity of the previously mentioned method of Kaur and Kumar (2012) was reduced by Ebrahimnejad (2014) by applying a fuzzy ranking function before applying fuzzified version of the traditional transportation algorithms. Therefore, the obtained crisp problem was solved via classical algorithms which need to perform less number of elementary operations and the same optimal solution was acquired without solving any fuzzy system and performing fuzzy arithmetic operations. A solution method was developed by Rani et al. (2014) to fully fuzzy unbalanced transportation problems without adding any dummy destination point. Actually, fuzzy transportation amounts were generated by that method which also gives the extra information on the excess availability of the sources should be transferred to which original destination for the possible future demand.

Different approaches based on fuzzy chance constrained programming, graded mean integrated value and fuzziness of total cost objective were proposed by Giri et al. (2015) to solve fully fuzzy fixed charge multi-item solid transportation problems including fuzzy decision variables. Deterministic equivalent models were derived by using credibility measure, fuzzy equality definition and arithmetic operations with respect to the decision maker's optimism degree. Then, the resulted transportation models were solved by Generalized Reduced Gradient (GRG) approach.

The model characteristics and solution methodologies to fuzzy transportation problem can be summarized as in Table 2.1. This table also classifies the above articles which are previously discussed. In most of the aforementioned articles, decision variables were considered as crisp values. However, for such transportation problems where all of the parameters, i.e., transportation costs, supply capacities and demands are fuzzy, decision maker should also consider transportation quantities as fuzzy variables. Thus, determining fuzzy efficient solutions for transportation problems with fuzzy decision variables is a relatively new and active research topic. There are just a few research papers on this subject.

2.3 Preliminaries and Some Background for CFA

In this section, some of the necessary background, definitions and fundamental notation regarding to both standard fuzzy arithmetic and CFA concept are presented.

Definition 2.3.1 A fuzzy number $\tilde{A} = (a, b, c)$ is called a triangular fuzzy number if its membership function is described as follows (Kauffmann & Gupta, 1985):

$$\mu_{\tilde{A}}(x) = \begin{cases} 1 - \frac{x-a}{b-a} & a \leq x \leq b \\ 1 - \frac{x-c}{b-c} & b \leq x \leq c \\ 0 & \text{Otherwise} \end{cases} \quad (2.1)$$

Definition 2.3.2 A triangular fuzzy number can be said to be a non-negative fuzzy number if and only if $a \geq 0$ (Kauffmann & Gupta, 1985; Kumar et al., 2010).

Definition 2.3.3 If left hand and right hand spreads of a triangular fuzzy number are equal ($b - a = c - b$), it is said to be symmetric; otherwise non-symmetric.

Table 2.1 Model characteristics and solution methodologies to fuzzy transportation problem in the current literature

Article	Type of the problem		Fuzzy terms				Type of fuzzy number	Solution itself		Solution methodology		
	Balanced	Unbalanced	Transport costs	Supply	Demand	Transport amount (decision variable)		Crisp	Fuzzy	Direct	Transform (Indirect)	Method
Chanas & Kuchta (1996)	•		•				L-L type FN	•			•	Bi-criterial problem by transportation simplex
Tada & Ishii (1996)	•	•		•	•		LMF	•			•	Parametric linear program
Jimenez & Verdegay (1998)	•			•	•		TPFN		•		•	Parametric programming approach
Jimenez & Verdegay (1999)	•			•	•		TPFN		•		•	Evolutionary algorithm based method to parametric program
Liu & Kao (2004)	•	•	•	•	•		TRFN & TPFN		•		•	Two-level mathematical programs & Extension principle
Ammar & Youness (2005)	•		•	•	•		TPFN		•		•	Parametric multi-objective non-linear programming approach
Gani & Razak (2006)	•			•	•		TPFN		•	•		Parametric approach
Buckley & Jowers (1992)	•		•	•	•		TRFN	•		•		Fuzzy Monte Carlo method
Lin (2009)	•			•	•		TRFN	•		•		Genetic algorithm with signed distance fuzzy ranking for selection & evaluation
Pandian & Natarajan (2010)	•		•	•	•	•	TPFN		•	•		Fuzzy zero point method
Kaur & Kumar (2011)	•		•	•	•	•	GTPFN		•	•		Fuzzy modified distribution method
Kumar & Kaur (2011)	•		•	•	•		TPFN		•	•	•	Fuzzy linear programming & classical transportation methods
Gani et al. (2011)	•	•	•	•	•	•	TRFN		•	•		Simplex type algorithm with two phases
Basirzadeh (2011)	•		•	•	•	•	TRFN & TPFN	•	•		•	Parametric fuzzy ranking method & classical transportation method
Gupta et al. (2012)	•	•	•	•	•	•	TPFN		•		•	Classical multi-objective linear programming approach
Kaur & Kumar (2012)	•		•				GTPFN		•	•		Generalized fuzzy modified distribution method
Chandran & Kandaswamy (2012)	•		•	•	•		IVFN		•	•		Fuzzy transportation algorithm with score fuzzy ranking method
Gupta & Kumar (2012)	•		•	•	•	•			•		•	Fuzzy programming approach
Ebrahimnejad (2014)	•		•				GTPFN		•	•		Standard transportation methods without fuzzy operators
Rani et al. (2014)		•	•	•	•	•	TPFN		•	•		Transportation algorithms with fuzzy dual variables
Giri et al. (2015)	•	•	•	•	•	•	TRFN		•		•	Mathematical programming with fuzzy chance constrained method
Proposed approach	•	•	•	•	•	•	TRFN		•	•		CFA based transformation and decoding algorithm with metaheuristic application

GTPFN – Generalized Trapezoidal Fuzzy Number, GFN – General Fuzzy Number, TPFN – Trapezoidal Fuzzy Number, TRFN – Triangular Fuzzy Number, LMF – Linear membership function

Definition 2.3.4 Standard fuzzy arithmetic operations between two triangular fuzzy numbers $\tilde{A} = (a, b, c)$ and $\tilde{B} = (x, y, z)$ can be defined based on the extension principle as follows (Lotfi et al., 2009; Gupta et al., 2012; Khan et al., 2013):

$$\text{Image, } \tilde{A} = (a, b, c), \quad -\tilde{A} = (-c, -b, -a) \quad (2.2)$$

$$\text{Addition, } \tilde{A} \oplus \tilde{B} = (a, b, c) \oplus (x, y, z) = (a + x, b + y, c + z) \quad (2.3)$$

$$\text{Subtraction, } \tilde{A} \ominus \tilde{B} = (a, b, c) \ominus (x, y, z) = (a - z, b - y, c - x) \quad (2.4)$$

$$\text{Multiplication, } \left\{ \begin{array}{l} k \otimes \tilde{A} = (k.a, k.b, k.c), \quad k > 0 \\ k \otimes \tilde{A} = (k.c, k.b, k.a), \quad k < 0 \\ \tilde{A} \otimes \tilde{B} = (a.x, b.y, c.z), \quad a \geq 0 \\ \tilde{A} \otimes \tilde{B} = (a.z, b.y, c.z), \quad a < 0, c \geq 0 \\ \tilde{A} \otimes \tilde{B} = (a.z, b.y, c.x), \quad c < 0 \end{array} \right\} \quad (2.5)$$

Definition 2.3.5 A fuzzy number $\tilde{A} = (a, b, c)$ can be defuzzified by considering the range of uncertainty (α) and risk tolerance of the decision maker (λ) as follows (Hus & Nian, 1997):

$$(d_{ij}^{\alpha})^{\lambda} = [\lambda \times a_{ij}^{\alpha} + (1 - \lambda) \times c_{ij}^{\alpha}] \quad 0 \leq \alpha, \lambda \leq 1 \quad (2.6)$$

Many usual principles for operation on real numbers don't extend to standard fuzzy arithmetic. In fact, addition and subtraction (respectively, multiplication and division) operations are not reciprocal for fuzzy numbers. In other words, it is not possible to solve inverse problems exactly using the standard fuzzy arithmetic operators (Gani & Assarudeen, 2012; Boukezzoula et al., 2014).

$$\tilde{A} \ominus \tilde{A} \neq 0 \quad (2.7)$$

$$\text{If } \tilde{A} \oplus \tilde{B} = \tilde{C}, \text{ then } \tilde{B} \neq \tilde{C} \ominus \tilde{A} \quad (2.8)$$

$$\text{If } \tilde{A} \otimes \tilde{B} = \tilde{C}, \text{ then } \tilde{B} \neq \frac{\tilde{C}}{\tilde{A}} \quad (2.9)$$

where $\tilde{C}$ is the solution of the fuzzy linear equation. Therefore, standard fuzzy arithmetic which performs unconstrained operations on fuzzy numbers may produce some counterintuitive results for many practical engineering applications. This is mainly due to the fact that known constraints related to the linguistic variables were not taken into account by standard fuzzy arithmetic.

These constraints are also referred to as “*requisite constraints*” and provide additional information about the relations between base variables of the linguistic terms (Klir & Cooper, 1996; Klir, 1997; Klir & Pan, 1998). Actually, each linguistic variable can be characterized in terms of a base variable. The actual value of the base variable associated to a linguistic variable is approximated by the fuzzy numbers. For example, given any pair of linguistic variables, A and B , defined for base variables a and b , respectively. The values of these base variables are in the set of real numbers $\mathbb{R}$. If there is no additional information between these base variables (a and b are independent variables), then the standard fuzzy arithmetic can be used for any of the arithmetic operations. In reality, the fuzzy intervals which we operate are not independent of each other. Thus, constrained fuzzy arithmetic is required for performing these operations.

Definition 2.3.6 In constrained fuzzy arithmetic, operations are defined on α -cut representation of fuzzy intervals (Klir, 1997). So, α -cuts of a triangular fuzzy number, $\tilde{A} = (a, b, c)$ can be denoted for all $\alpha \in (0,1]$ by the following formula:

$$A^\alpha = [a + (b - a)\alpha, c - (c - b)\alpha] \quad (2.10)$$

Definition 2.3.7 Basic constrained fuzzy arithmetic operations on the α -cuts of $\tilde{A}$ and $\tilde{B}$ can be defined for all $\alpha \in (0,1]$ as follows (Klir & Cooper, 1996):

$$(\tilde{A} \circ \tilde{B})_C^\alpha = \{a \circ b \mid \langle a, b \rangle \in (A^\alpha \times B^\alpha) \cap C \text{ or } C^\alpha \} \quad (2.11)$$

where $(\tilde{A} \circ \tilde{B})_C^\alpha$ represents the α -cut of the arithmetic operation $\circ$ which is one of the fuzzy arithmetic operations ($\otimes, \oplus, \ominus, \oslash$), of fuzzy numbers $\tilde{A}$ and $\tilde{B}$, under a given crisp C or fuzzy constraint C^α between the associated base variables a and b .

If there is a crisp equality relation between these base variables $C: a = b$, this is called as equality constraint (E) (Klir, 1997). In addition, if someone deals with the algebraic expressions with fuzzy numbers and some of the fuzzy numbers in this algebraic expression are represented by the same symbols, then these numbers treated as the numbers constrained by the equality relation (Klir & Pan, 1998). This is a general rule called “*equality rule*” in constrained fuzzy arithmetic.

Definition 2.3.8 The constrained operations on $\tilde{A}$ where $\tilde{A} \odot \tilde{A}$ are subject to the equality constraint can be given as follows (Klir, 1997; Klir & Cooper, 1996):

$$(\tilde{A} \oplus \tilde{A})_E^\alpha = \{a \oplus a \mid a \in A^\alpha\} = [2\underline{a}, 2\bar{a}]^\alpha \quad (2.12)$$

$$(\tilde{A} \ominus \tilde{A})_E^\alpha = \{a \ominus a \mid a \in A^\alpha\} = 0 \quad (2.13)$$

$$(\tilde{A} \otimes \tilde{A})_E^\alpha = \begin{cases} [\bar{a}^2, \underline{a}^2]^\alpha & \text{if } \bar{a} < 0 \\ [\underline{a}^2, \bar{a}^2]^\alpha & \text{if } \underline{a} > 0 \\ [0, \max(\underline{a}^2, \bar{a}^2)]^\alpha & \text{if } 0 \in [\underline{a}, \bar{a}]^\alpha \end{cases} \quad (2.14)$$

$$(\tilde{A} \oslash \tilde{A})_E^\alpha = \{a \oslash a \mid a \in A^\alpha, 0 \notin A^\alpha \text{ for all } \alpha \in (0,1]\} = 1 \quad (2.15)$$

Remark 2.3.1 When applying the equality constraint, it is more suggestive to solve equations including fuzzy arithmetic expressions (Klir & Pan, 1998). The previously given equations can be solved as follows under the equality constraint:

$$\text{If } \tilde{A} \oplus \tilde{B} = \tilde{C}, \text{ then } \tilde{B} = \tilde{C} \ominus \tilde{A} \quad (2.16)$$

$$\text{If } \tilde{A} \otimes \tilde{B} = \tilde{C}, \text{ then } \tilde{B} = \frac{\tilde{C}}{\tilde{A}} \quad (2.17)$$

Definition 2.3.9 In some practical applications, there may be crisp inequality relation between the base variables of the fuzzy intervals. For example, one of the base variables may be smaller/greater than or equal to another base variable. In this case, this useful information should also be taken into account during the arithmetic operations. Some necessary fuzzy arithmetic operations under crisp inequality constraints can be summarized for $\tilde{A}$ and $\tilde{B}$ fuzzy intervals and their base variables, a and b as follows (Klir, 1997; Klir & Cooper, 1996):

$$(A \oplus B)_{a \leq b}^\alpha = \begin{cases} \text{no solution} & \text{when } \bar{b}(\alpha) \leq \underline{a}(\alpha) \\ [\underline{a}(\alpha) + \underline{b}(\alpha), 2\bar{b}(\alpha)] & \text{when } \underline{a}(\alpha) \leq \underline{b}(\alpha) \leq \bar{b}(\alpha) \leq \bar{a}(\alpha) \\ [2\underline{a}(\alpha), 2\bar{b}(\alpha)] & \text{when } \underline{b}(\alpha) \leq \underline{a}(\alpha) \leq \bar{b}(\alpha) \leq \bar{a}(\alpha) \\ [2\underline{a}(\alpha), \bar{a}(\alpha) + \bar{b}(\alpha)] & \text{when } \underline{b}(\alpha) \leq \underline{a}(\alpha) \leq \bar{a}(\alpha) \leq \bar{b}(\alpha) \\ [\underline{a}(\alpha) + \underline{b}(\alpha), \bar{a}(\alpha) + \bar{b}(\alpha)] & \text{when } \underline{a}(\alpha) \leq \underline{b}(\alpha) \leq \bar{a}(\alpha) \leq \bar{b}(\alpha) \\ [\underline{a}(\alpha) + \underline{b}(\alpha), \bar{a}(\alpha) + \bar{b}(\alpha)] & \text{when } \underline{a}(\alpha) \leq \bar{a}(\alpha) \leq \underline{b}(\alpha) \leq \bar{b}(\alpha) \end{cases} \quad (2.18)$$

$$(A \ominus B)_{a \leq b}^\alpha = \begin{cases} \text{no solution} & \text{when } \bar{b}(\alpha) \leq \underline{a}(\alpha) \\ [\underline{a}(\alpha) - \bar{b}(\alpha), \bar{a}(\alpha) - \underline{b}(\alpha)] & \text{when } \underline{a}(\alpha) \leq \bar{a}(\alpha) \leq \underline{b}(\alpha) \leq \bar{b}(\alpha) \\ [\underline{a}(\alpha) - \bar{b}(\alpha), 0] & \text{Otherwise} \end{cases} \quad (2.19)$$

$$(B \ominus A)_{a \leq b}^\alpha = \begin{cases} \text{no solution} & \text{when } \bar{b}(\alpha) \leq \underline{a}(\alpha) \\ [\underline{b}(\alpha) - \bar{a}(\alpha), \bar{b}(\alpha) - \underline{a}(\alpha)] & \text{when } \underline{a}(\alpha) \leq \bar{a}(\alpha) \leq \underline{b}(\alpha) \leq \bar{b}(\alpha) \\ [0, \bar{b}(\alpha) - \underline{a}(\alpha)] & \text{Otherwise} \end{cases} \quad (2.20)$$

where “no solution” displays the inconsistent conditions with the inequality relation.

Definition 2.3.10 Occasionally, the base variables may be constrained in a fuzzy way. Consider that ranges of base variables a and b are defined with associated fuzzy numbers $\tilde{A}$ and $\tilde{B}$. There may be a fuzzy relation between these base variables a and b . This relation can be implied as in the linguistic term “ a is approximately equal to b ”. The generalized form of this fuzzy equality constraint can be defined in terms of the α -cuts of the fuzzy numbers as follows:

$$(\tilde{A} \odot \tilde{B})_{\tilde{E}}^\alpha = \{a * b | \langle a, b \rangle \in (A^\alpha \times B^\alpha) \cap \tilde{E}^\alpha\} \quad (2.21)$$

Definition 2.3.11 For such a fuzzy equality constraint, it is plausible to approximate this linguistic expression “approximately equal” by following membership function (Klir and Pan, 1998).

$$\tilde{E}(a, b) = \max\left(0, 1 - \frac{|a - b|}{\Delta}\right) \quad (2.22)$$

The membership function of this fuzzy relation can also be visualized as depicted in Figure 2.1. In this figure, Δ is a positive real number whose value is chosen in each context so as to make fuzzy relation $(\tilde{E})$ a good representation of linguistic term “approximately equal” in that content (Klir & Cooper, 1996).

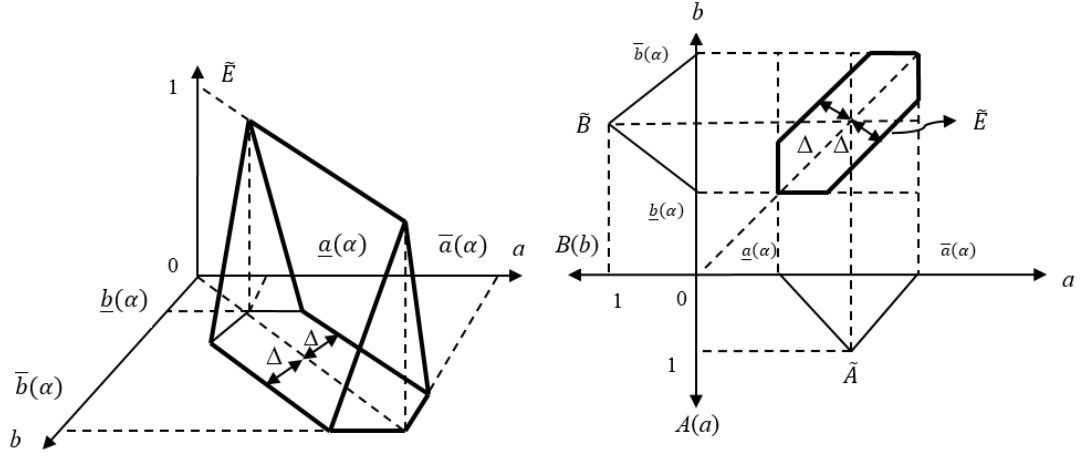


Figure 2.1 Membership function of fuzzy equality relation “a is approximately equal to b”

Example 2.3.1 In order to illustrate the fuzzy equality constraint between the base variables, let $\tilde{A}$ and $\tilde{B}$ be the given triangular fuzzy numbers: $\tilde{A} = \tilde{B} = (6, 7, 8)$ and $A^\alpha = B^\alpha = [6 + \alpha, 8 - \alpha]$. When the standard fuzzy arithmetic without the fuzzy constraint is performed, that is $\tilde{A} \ominus \tilde{B} = \tilde{B} \ominus \tilde{A} = (-2, 0, 2)$. However, with knowing the additional information that base variables of these fuzzy numbers are approximately equal, the fuzzy constraint can be expressed for the same fuzzy arithmetic operation as follows (Klir, 1997):

$$(\tilde{A} \ominus \tilde{B})_{\tilde{E}}^\alpha = (\tilde{B} \ominus \tilde{A})_{\tilde{E}}^\alpha = [\underline{a}(\alpha) - \underline{b}(\alpha) - \Delta\sqrt{2}(1 - \alpha), \bar{a}(\alpha) - \bar{b}(\alpha) + \Delta\sqrt{2}(1 - \alpha)]^\alpha \quad (2.23)$$

For the given fuzzy numbers and $\Delta = 0.1$ ($\Delta < \sqrt{2}$) which takes a sufficiently small value so that all the α -cuts of these triangular fuzzy numbers are constrained through the α -cuts of $\tilde{E}$ for all $\alpha \in (0, 1]$, we obtain:

$$(\tilde{A} \ominus \tilde{B})_{\tilde{E}}^\alpha = (\tilde{B} \ominus \tilde{A})_{\tilde{E}}^\alpha = [-0.1\sqrt{2}(1 - \alpha), 0.1\sqrt{2}(1 - \alpha)]^\alpha = (-0.14, 0, 0.14) \quad (2.24)$$

Remark 2.3.2 In the proposed CFA based transformation approach, a conjugate model is required in order to perform the fuzzy arithmetic operations under requisite constraints. The conjugate versions of the following fuzzy linear constraints can also be written as follows:

$$\tilde{x}_i \lesssim \tilde{b}_i \Leftrightarrow (\tilde{b}_i \ominus \tilde{x}_i)_{x_i \leq b_i} \geq 0 \quad \forall i \quad (2.25)$$

$$\tilde{y}_j \gtrsim \tilde{d}_j \Leftrightarrow (\tilde{d}_j \ominus \tilde{y}_j)_{y_j \geq d_j} \leq 0 \quad \forall j \quad (2.26)$$

2.4 Description and Formulation of Fully Fuzzy Transportation Problems

In real life settings of transportation problem, decision makers may face with many uncertainties on the cost of transportation, availability of materials (supply capacity of the sources), demands of destinations etc. due to the many uncontrollable factors. In other words, the decision makers cannot exactly know the parameters of a transportation problem in reality. Additionally, these parameters are not stable since this imprecision may follow from the lack of exact information or data, uncertainty in judgment, high information cost or an outcome of certain flexibility needed by a source company or demand marketplace. This imprecision embedded into the parameters may not be of a probabilistic type, so this type of uncertainty can be handled via fuzzy parameters (Gani et al., 2011; Chandran & Kandaswamy, 2012; Rani et al., 2014). The uncontrollable factors which may cause some sort of ambiguity in transportation problems were explained by Kumar and Kaur (2011) as follows:

- There is not an expert which exactly knows the unit transportation cost of a first time transportation operation,
- There may be some sort of ambiguity about the demand of a newly introduced product to the market,
- There exists uncertainty regarding product availability at a source or supplier due to the time factor. For example, the promised quantity of a product may not be available at the exact amount for some reasons at the time of delivery,
- Additionally, decision variables (which represent the transportation quantities from different sources to the various destinations) should also be fuzzy in such transportation problems where all of the parameters are stated as fuzzy.

In that way, under fuzzy demand and fuzzy capacity conditions providing crisp transportation amounts may not be truly appropriate. Moreover, vague amounts of products may be lost or perished because of many reasons during transportation. It is also possible to carry out some revisions on flow quantities during the planning horizon. Therefore, providing fuzzy solutions may be more appropriate for decision maker(s). Since the objective function value of the examined problem is also fuzzy, decision makers can have an idea about the range of the objective function values.

The examined fully fuzzy transportation problem and configuration of a transportation network can be portrayed as in Figure 2.2.

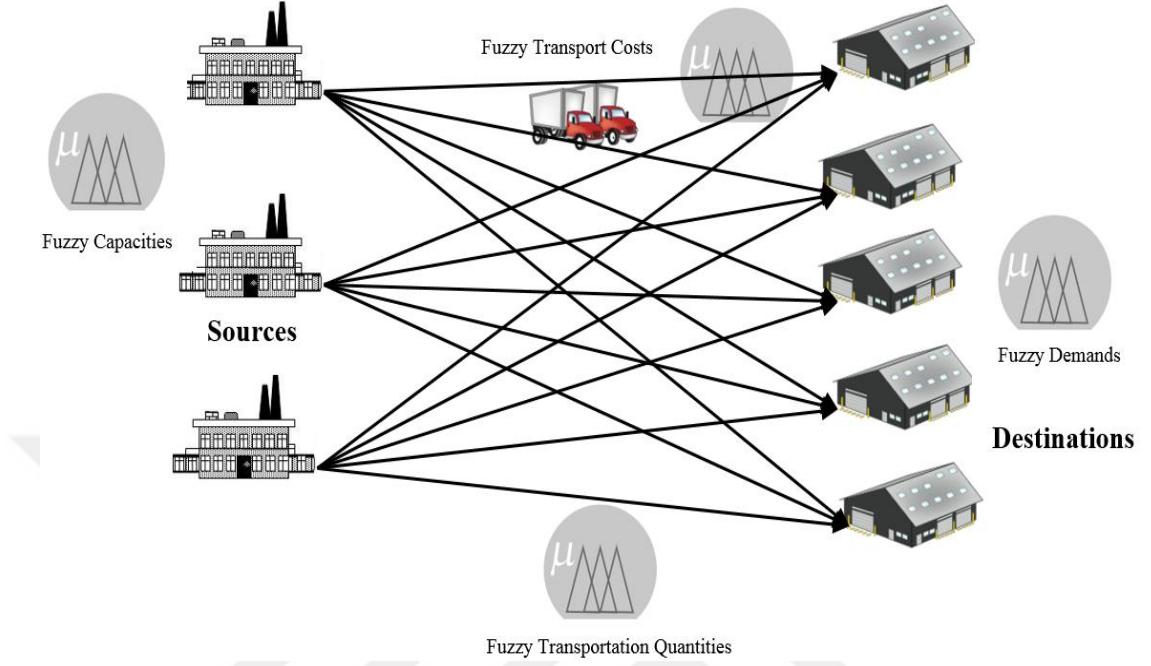


Figure 2.2 Depiction of the fully fuzzy transportation problem

The mathematical formulation of the fully fuzzy transportation problem with triangular fuzzy numbers can be expressed as follows:

$$\text{Minimize } \tilde{Z} \approx \sum_{i=1}^S \sum_{j=1}^D \tilde{c}_{ij} \otimes \tilde{x}_{ij} \quad (2.27)$$

Subject to:

$$\sum_{j=1}^D \tilde{x}_{ij} \lesssim \widetilde{Cap}_i \quad \forall i \quad (2.28)$$

$$\sum_{i=1}^S \tilde{x}_{ij} \gtrsim \widetilde{De}_j \quad \forall j \quad (2.29)$$

$$\tilde{x}_{ij} \text{ are non-negative fuzzy numbers } \quad \forall i \in S, \forall j \in D \quad (2.30)$$

where S and D denote the total number of sources and destinations, respectively. Moreover, $\tilde{c}_{ij}$ represents the unit transportation cost from source node i to destination node j , $\widetilde{Cap}_i$ is the product availability of source i and demand of destination j is given by $\widetilde{De}_j$, respectively. For a fully fuzzy transportation problem instance, it was also

emphasized by Oheigearthaigh (1982) that quantity of transported products and transportation costs should not be negative fuzzy numbers since they have no physical meanings. Instead of a FFTP, when the problem is stated as a fully fuzzy transshipment problem, then the following constraint should also be added to the above formulation for the transshipment nodes, $j \in T$:

$$\sum_{(i,j) \in A} \tilde{x}_{ij} \cong \sum_{(j,k) \in A} \tilde{x}_{jk} \quad \forall j \in T \quad (2.31)$$

In order to solve and analyze the aforementioned fully fuzzy transportation problem by considering the decision maker's attitude toward risk, it may also be required to classify these kinds of problems according to the balance between fuzzy “total capacities” and fuzzy “total demands”. Although, the FFTP's are classified as balanced and unbalanced fuzzy transportation problems by Kaur and Kumar (2011), we investigated the problem under five different types:

Type-1: FFTP where the fuzzy total capacities are same with fuzzy total demands, i.e., they are defined by same fuzzy number where the fuzzy total capacities are the same with the fuzzy total demands $\left(\sum_j \underline{De}_j = \sum_i \underline{Cap}_i \leq \sum_j \overline{De}_j = \sum_i \overline{Cap}_i\right)$ is named as balanced case (Kumar & Kaur, 2011; Gupta et al., 2012). In other words, these parameters are defined by the same fuzzy number. The membership functions of fuzzy total demands and capacities for balanced fully fuzzy transportation case are given in Figure 2.3.

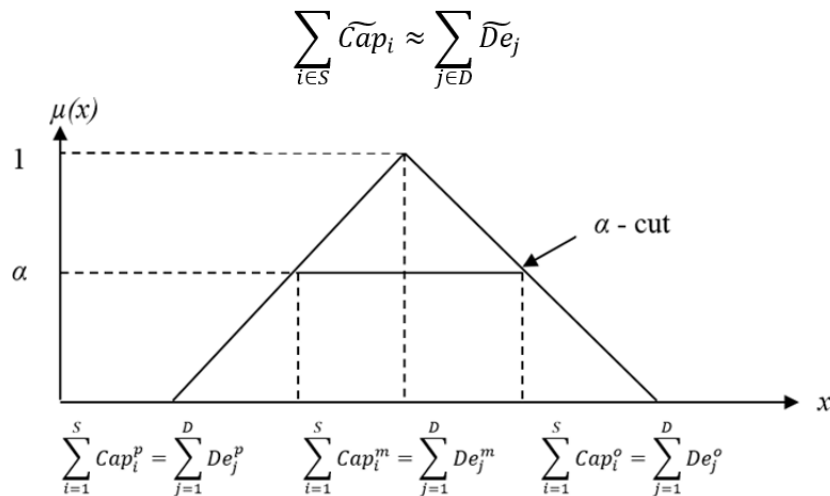


Figure 2.3 Membership functions of type-1 balanced fully fuzzy transportation case

In fact, for this problem type, it is not possible to obtain a risk-free solution which is usually desired by a risk-averse person (for different α -cut values where $\alpha < 1$). In other words, the only risk-free, i.e. capacity unavailability and/or unsatisfactory demand, solution is at $\alpha = 1$ level as depicted in Figure 2.3. Let's consider a balanced FFTP consisting of one source and one destination. The maximal and minimal risky situations (unavailability of sources and unsatisfactory demand of destinations) for this case can be demonstrated as in Figure 2.4.

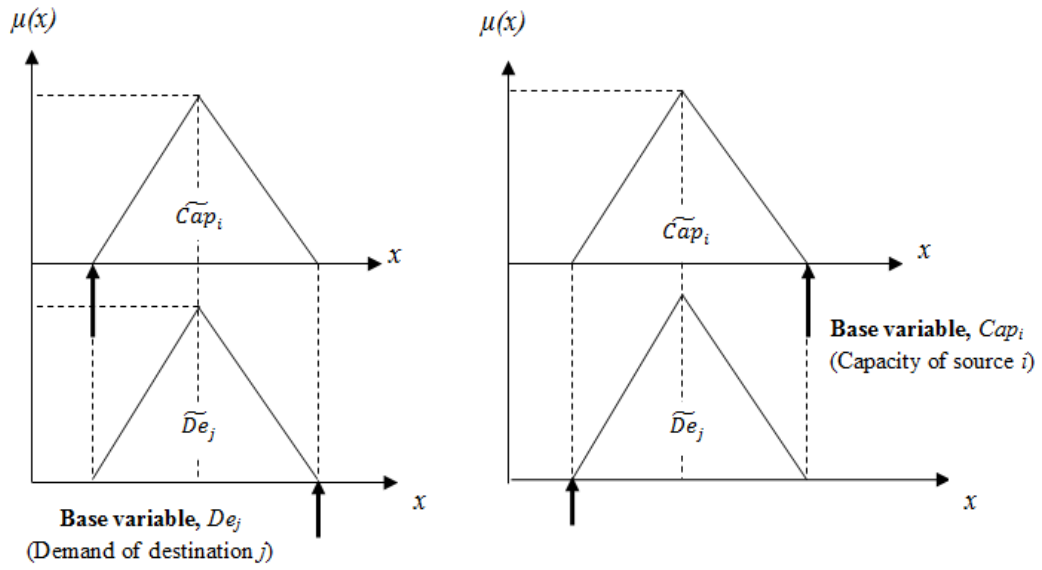


Figure 2.4 Most and least risky situations for type-1 balanced transportation case

It is obvious from Figure 2.4 that it isn't possible to produce feasible solutions for this transportation case under the specific crisp relations between the associated base variables ($\sum_j x_{ij} \leq Cap_i \quad \forall i$ and $\sum_i x_{ij} \geq De_j \quad \forall j$). On the other hand, one can generate feasible solutions when a fuzzy relation between these base variables is defined by the decision maker.

Type-2: FFTP where fuzzy total capacities are less than fuzzy total demands ($\sum_i \overline{Cap_i} < \sum_j \underline{De_j}$). For this type of FFTPs, the decision maker cannot provide any feasible solution at any α -level. Because, fuzzy demands cannot be satisfied by the fuzzy capacities as it is shown by Figure 2.5.

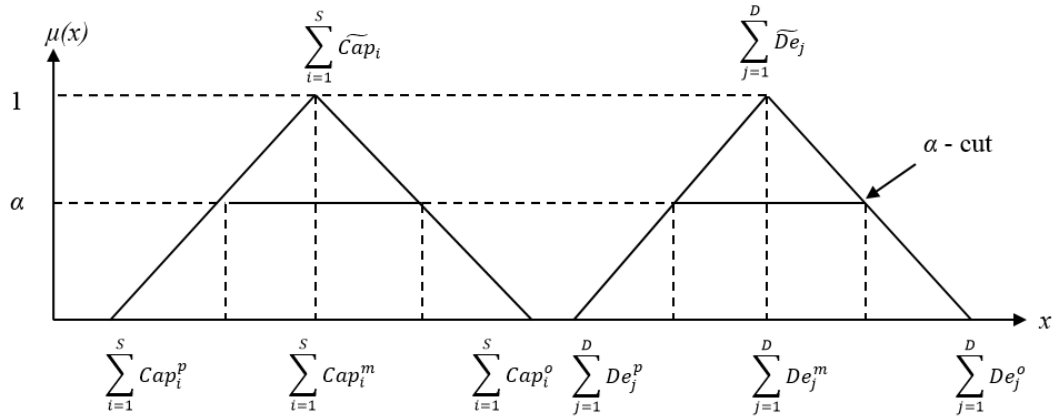


Figure 2.5 Type-2 fully fuzzy transportation problem

Type-3: FFTP where the fuzzy total demands are less than fuzzy total capacities as shown in Figure 2.6 ($\sum_j \overline{De_j} \leq \sum_i \underline{Cap_i}$). In the realization phase of this FFTP type, a risk-free solution may be obtained when it is required by a risk-averse decision maker. It may be possible to meet all demands for all situations in this transportation case. However, it is also possible to obtain risky solutions for this type of problem.

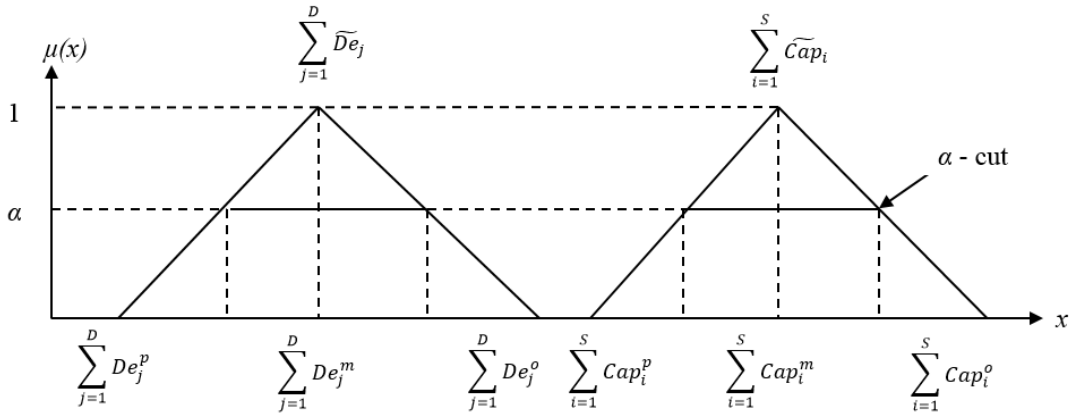


Figure 2.6 Type-3 fully fuzzy transportation problem

Type-4: FFTP where the fuzzy total demands are approximately less than and equal to fuzzy total capacities, i.e., there is an intersection between the fuzzy total capacities and fuzzy total demands ($\sum_j \underline{De_j} \leq \sum_i \underline{Cap_i} \leq \sum_j \overline{De_j} \leq \sum_i \overline{Cap_i}$). Decision maker cannot provide a fully risk-free solution for all α -cut levels as depicted in Figure 2.7. Because, under some value of α -cut where intersection starts, there is a risk of unsatisfactory demands (i.e., $\sum_i \underline{Cap_i} \leq \sum_j \overline{De_j}$). In other words, the crisp relation

between the associated base variables cannot be satisfied below this α -cut level. However, it is possible to obtain partially risk-free solutions according to the risk attitude of the decision maker. Thus, the region A can be called as the risky region for this type of FFTPs. Above this α -cut level, one can generate risk-free solutions.

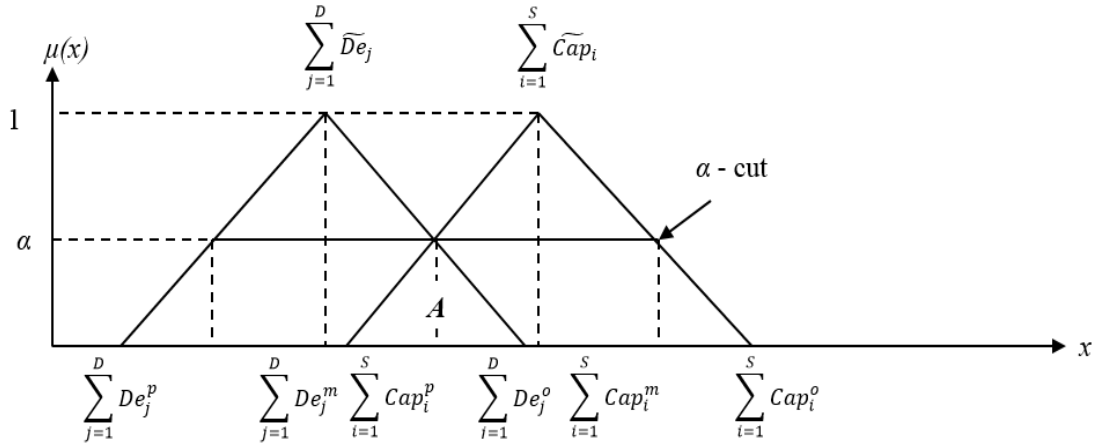


Figure 2.7 Type-4 fully fuzzy transportation problem

Type-5: FFTP where fuzzy total capacities are approximately less than or equal to fuzzy total demands ($\sum_i \underline{Cap}_i \leq \sum_j \underline{De}_j \leq \sum_i \overline{Cap}_i \leq \sum_j \overline{De}_j$). As it is seen from Figure 2.8, it cannot be generated feasible solutions above the α -cut level. However, there is chance to provide feasible solutions in region B. It should also be mentioned here that none of the existing methods (Ezzati et al., 2015; Kumar & Kaur, 2011) in the literature can provide any feasible solution for this transportation case.

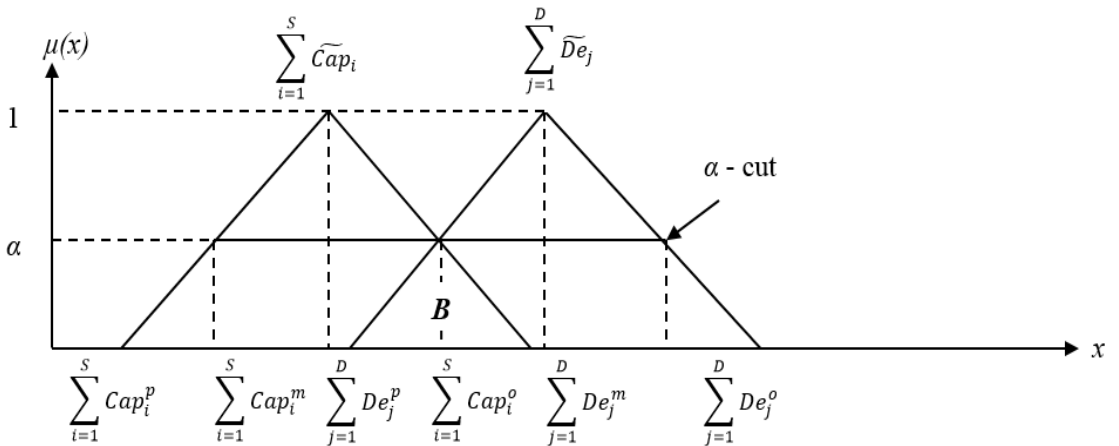


Figure 2.8 Type-5 fully fuzzy transportation problem

2.5 A Constrained Fuzzy Arithmetic Based Indirect Solution Approach for Fully Fuzzy Transportation Problems

In this section, a constrained fuzzy arithmetic based transformation approach is introduced for solving FFTPs. The proposed method mainly depends on the fuzzy arithmetic operations under the given crisp or fuzzy relations between the associated base variables. Actually, crisp/fuzzy constraints represent the additional information provided by the decision maker according to his/her risk attitude. In order to obtain a realizable solution for a given FFTP for a risk-averse person, the conjugate model is solved by utilizing the constrained fuzzy arithmetic approach with the crisp constraint sets $(\sum_j x_{ij} \leq Cap_i \quad \forall i \text{ and } \sum_i x_{ij} \geq De_j \quad \forall j)$. Thereby, capacity availability and fully demand satisfaction are guaranteed by this approach. Subsequently, constrained fuzzy arithmetic operations with fuzzy relations $(\sum_j x_{ij} \approx Cap_i \quad \forall i \text{ and } \sum_i x_{ij} \approx De_j \quad \forall j)$ between the base variables of the uncertain parameters and/or decision variables is also used to provide fuzzy efficient solutions for decision maker(s) who are risk-seekers (Subulan & Baykasoğlu, 2014).

2.5.1 The Proposed Constrained Fuzzy Arithmetic Based Indirect Solution Approach under Crisp Inequality Constraints

In a FFTP, a risk-averse decision maker may have exact judgments such as “transportation quantity from a source should be less than or equal to the capacity of that source” and “transportation quantity to a destination should be greater than or equal to the demand of that destination”. Therefore, in order to yield feasible and reliable solutions for a risk-averse person, it is required to solve the following conjugate version of the FFTP model given in equations (2.32) - (2.35) by utilizing the CFA approach. Actually, this conjugate model is required for performing the constrained fuzzy arithmetic operations. The mentioned conjugate model of the stated FFTP with the aid of crisp inequality constraints can be formulated as follows:

$$\text{Minimize } \tilde{Z} \approx \sum_{i=1}^S \sum_{j=1}^D \tilde{c}_{ij} \otimes \tilde{x}_{ij} \quad (2.32)$$

$$\left(\widetilde{Cap}_i \ominus \sum_{j=1}^D \tilde{x}_{ij} \right)_{\sum_j x_{ij} \leq Cap_i} \geq 0 \quad \forall i \quad (2.33)$$

$$\left(\widetilde{De}_j \ominus \sum_{i=1}^S \tilde{x}_{ij} \right)_{\sum_i x_{ij} \geq De_j} \leq 0 \quad \forall j \quad (2.34)$$

$$\tilde{x}_{ij} \text{ are non - negative fuzzy numbers } \quad \forall i \in S, \forall j \in D \quad (2.35)$$

where the values of these uncertain parameters and decision variables ($\widetilde{Cap}_i$, $\widetilde{De}_j$ and $\tilde{x}_{ij}$) are fuzzy numbers and the values of the corresponding base variables (Cap_i , De_j and x_{ij}) are in the set $\mathbb{R}$ of real numbers. The constraint (2.33) ensures that remaining fuzzy capacities should be greater than or equal to zero under the crisp constraint set. This constraint guarantees the capacity availability of the sources. Similarly, according to constraint (2.34), remaining fuzzy demands should be less than or equal to zero under the crisp relation. Thus, fully demand satisfaction can be guaranteed by this constraint. When the problem is a fully fuzzy transshipment problem, then the following constraint should be added to the above conjugate model where the transshipment node $j \in T$:

$$\left(\sum_{(i,j) \in A} \tilde{x}_{ij} \ominus \sum_{(j,k) \in A} \tilde{x}_{jk} \right)_{\sum_i x_{ij} = \sum_k x_{jk}} = 0 \quad \forall j \in T \quad (2.36)$$

All of the above fuzzy subtraction operations for calculating the fuzzy remaining capacities and demands are performed by making use of CFA concept. This provides positive remaining capacity and negative remaining demand which are generally desired by a risk-averse decision maker for real-life settings. With the usage of this approach, the dependence between the fuzzy numbers which we operate can be taken into account while performing the fuzzy arithmetic operations. Additionally, the risks related to the capacity unavailability and demand unsatisfactory can be avoided. It should be mentioned here again that, uncertainty embedded in the decision variables is so important for a risk-averse decision maker. Generation of excessively imprecise results which are not desired by these kinds of decision makers can be prevented by the proposed method. A general way of calculating the fuzzy remaining capacities via CFA with different α -cut levels are given by the following Equations (2.37) - (2.39).

$$\widetilde{Cap}_i = (Cap_i^p, Cap_i^m, Cap_i^o) = [\underline{Cap}_i, \overline{Cap}_i]^\alpha = \quad (2.37)$$

$$[Cap_i^p + (Cap_i^m - Cap_i^p)\alpha, Cap_i^o - (Cap_i^o - Cap_i^m)\alpha]$$

$$\sum_{j=1}^D \tilde{x}_{ij} = \left(\sum_{j=1}^D (x_{ij}^p, x_{ij}^m, x_{ij}^o) \right) = \left[\sum_{j=1}^D x_{ij}, \overline{\sum_{j=1}^D x_{ij}} \right]^\alpha = \quad (2.38)$$

$$\left[\sum_{j=1}^D x_{ij}^p + \left(\sum_{j=1}^D x_{ij}^m - \sum_{j=1}^D x_{ij}^p \right) \alpha, \sum_{j=1}^D x_{ij}^o - \left(\sum_{j=1}^D x_{ij}^o - \sum_{j=1}^D x_{ij}^m \right) \alpha \right]$$

$$\left(\widetilde{Cap}_i \ominus \sum_{j=1}^D \tilde{x}_{ij} \right)_{\sum_j x_{ij} \leq Cap_i}^\alpha =$$

$$\begin{cases} \text{no solution} & \text{case 1: when } \overline{Cap}_i(\alpha) \leq \sum_{j=1}^D x_{ij}(\alpha) \\ \left[\underline{Cap}_i(\alpha) - \sum_{j=1}^D x_{ij}(\alpha), \overline{Cap}_i(\alpha) - \sum_{j=1}^D x_{ij}(\alpha) \right] & \text{when } \sum_{j=1}^D x_{ij}(\alpha) \leq \underline{Cap}_i(\alpha) \leq \overline{Cap}_i(\alpha) \\ \left[0, \overline{Cap}_i(\alpha) - \sum_{j=1}^D x_{ij}(\alpha) \right] & \text{case 3: otherwise} \end{cases} \quad (2.39)$$

As it is clearly seen from Figure 2.9, there must be a crisp relation between the base variables namely capacity and total outgoing flow of each source. With the usage of this crisp constraint, total outgoing flows from any source will be less than or equal to the capacity of that source. Consider the triangular fuzzy intervals, $\widetilde{Cap}_i$, $\tilde{x}_{ij}$, respectively and assume that the associated base variables satisfy the inequality: $\sum_j x_{ij} \leq Cap_i \quad \forall i$. It should also be emphasized that examined crisp constraint in Eq. (2.39) involves summation of different base variables $(\sum_j x_{ij})$ related to the uncertain decision variables, i.e., $(\tilde{x}_{ij})$. Since all of these decision variables represent different transportation quantities from source i to destination j , it is not needed to solve any optimization problem as implied by Klir and Cooper (1996), Klir, (1997), Klir and Pan (1998) while calculating end points of this summation (total outgoing flows from the source i) in Equation (2.38). Because, no variables appears in

that summation more than once and so the equality constraint is not applicable for this kind of function. Also, there is no interdependence between these variables.

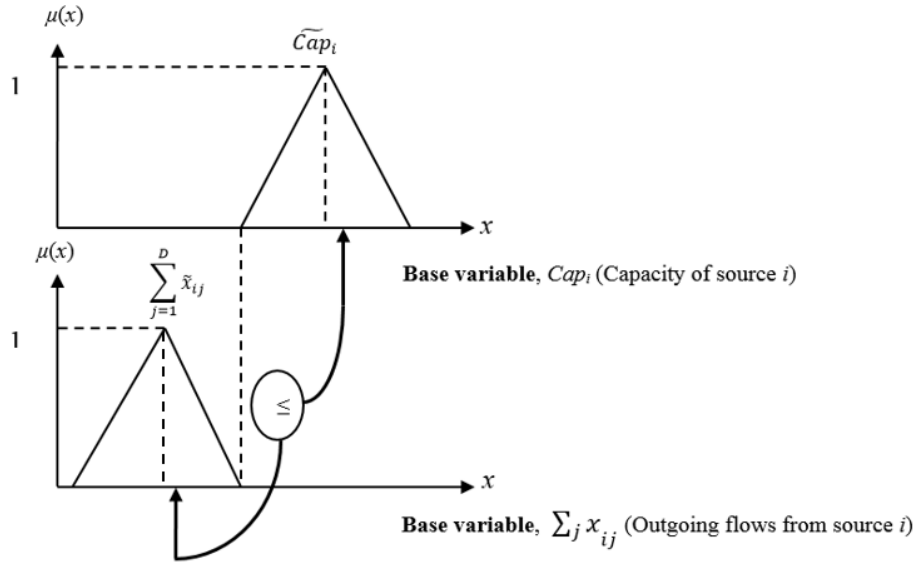


Figure 2.9 CFA approach for capacity availability under crisp relation

In order to see the different cases included in the fuzzy subtraction operation under crisp inequality, Equation (2.39) is illustrated by Figures 2.10, 2.11 and 2.12. Case-1 represents infeasible solution of the problem.

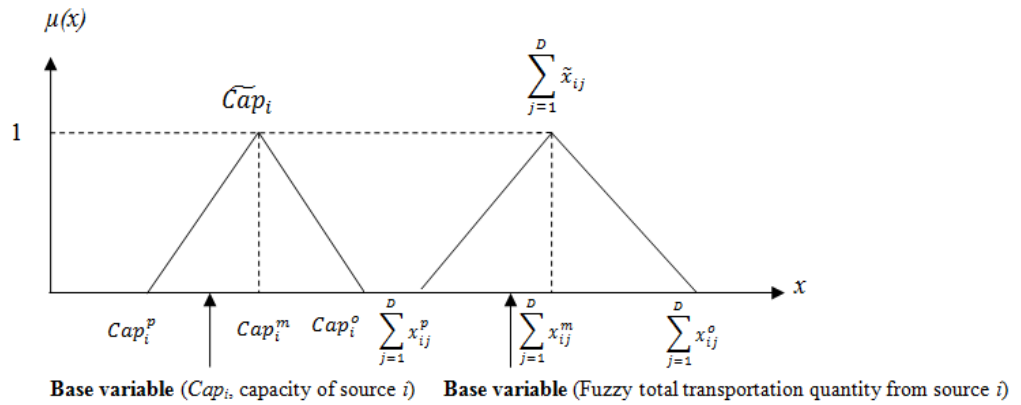


Figure 2.10 Fuzzy subtraction operation under crisp constraint for capacity availability check (Case-1)

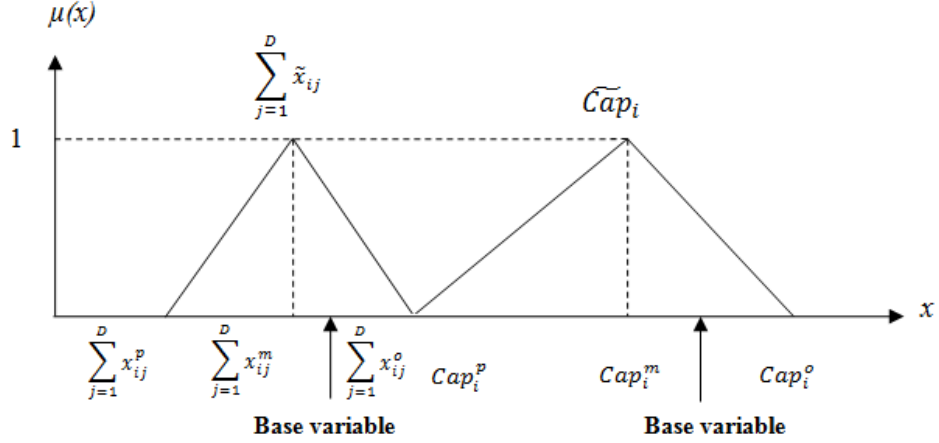


Figure 2.11 Fuzzy subtraction operation under crisp constraint for capacity availability check (Case-2)

The operations in case-2 correspond to the standard fuzzy arithmetic and also lead to risk-free solution. In case-3, where the membership functions of the fuzzy capacity and decision variables intersect reflects the presence of the risk. Since all of the existing methods in the literature utilize the extension principle, they may not generate appropriate solutions for the FFTPs that correspond to case-3. In other words, this risk embedded case is not taken into account by the standard fuzzy arithmetic. However, this case can be handled by CFA.

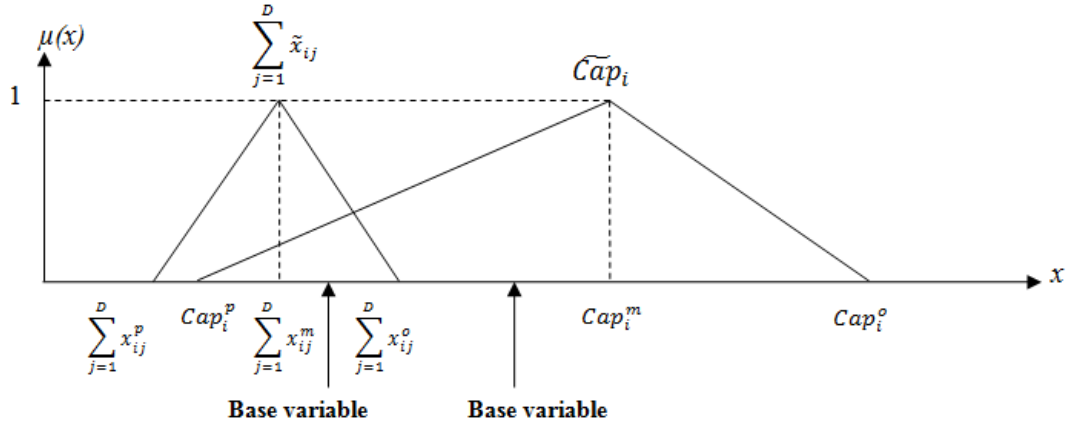


Figure 2.12 Fuzzy subtraction operation under crisp constraint for capacity availability check (Case-3)

In a similar way, calculation of the fuzzy remaining demands via CFA approach when employing the α -cut representation can be seen from Equations (2.40) - (2.42). In fact, all of these crisp inequalities are utilized in (2.39) and (2.42) are problem specific constraints. This means that total incoming flows to any destination should

always be greater than or equal to the demand of that destination. In fact, Figure 2.13 displays the crisp constraint on the fuzzy subtraction operation in Eq. 2.42.

$$\begin{aligned} \widetilde{De}_j &= (De_j^p, De_j^m, De_j^o) = [\underline{De}_j, \overline{De}_j]^\alpha = \\ &[De_j^p + (De_j^m - De_j^p)\alpha, De_j^o - (De_j^o - De_j^m)\alpha] \end{aligned} \quad (2.40)$$

$$\begin{aligned} \sum_{i=1}^S \tilde{x}_{ij} &= \left(\sum_{i=1}^S (x_{ij}^p, x_{ij}^m, x_{ij}^o) \right) = \left[\sum_{i=1}^S x_{ij}, \sum_{i=1}^S x_{ij} \right]^\alpha = \\ &= \left[\sum_{i=1}^S x_{ij}^p + \left(\sum_{i=1}^S x_{ij}^m - \sum_{i=1}^S x_{ij}^p \right) \alpha, \sum_{i=1}^S x_{ij}^o - \left(\sum_{i=1}^S x_{ij}^o - \sum_{i=1}^S x_{ij}^m \right) \alpha \right] \end{aligned} \quad (2.41)$$

$$\left(\widetilde{De}_j \ominus \sum_{i=1}^S \tilde{x}_{ij} \right)_{\sum_i x_{ij} \geq De_j}^\alpha = \left\{ \begin{array}{ll} \text{no solution} & \text{Case1: when } \sum_{i=1}^S x_{ij}(\alpha) \leq \underline{De}_j(\alpha) \\ \left[\underline{De}_j(\alpha) - \sum_{i=1}^S x_{ij}(\alpha), \overline{De}_j(\alpha) - \sum_{i=1}^S x_{ij}(\alpha) \right] & \text{when } \underline{De}_j(\alpha) \leq \overline{De}_j(\alpha) \leq \sum_{i=1}^S x_{ij}(\alpha) \leq \sum_{i=1}^S x_{ij}(\alpha) \\ \left[\underline{De}_j(\alpha) - \sum_{i=1}^S x_{ij}(\alpha), 0 \right] & \text{Case3: otherwise} \end{array} \right\} \quad (2.42)$$

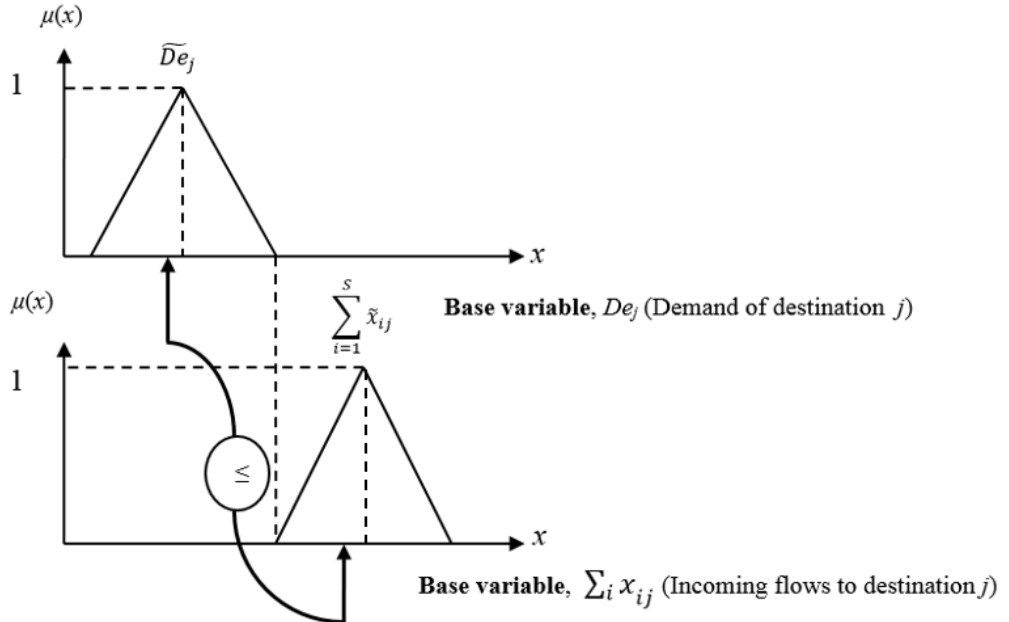


Figure 2.13 CFA approach for demand satisfaction under crisp relation

The steps of the proposed CFA based indirect solution approach to solve FFTPs for the risk-averse decision maker(s) are introduced as follows (Subulan & Baykasoğlu, 2014):

Step 1: The conjugate version of the given FFTP can be written as follows without using any fuzzy ranking function:

$$\text{Minimize } \sum_{i=1}^S \sum_{j=1}^D \tilde{c}_{ij} \otimes \tilde{x}_{ij} \quad (2.43)$$

Subject to:

$$\left(\widetilde{Cap}_i \ominus \sum_{j=1}^D \tilde{x}_{ij} \right)_{\sum_j x_{ij} \leq Cap_i} \geq 0 \quad \forall i \quad (2.44)$$

$$\left(\widetilde{De}_j \ominus \sum_{i=1}^S \tilde{x}_{ij} \right)_{\sum_i x_{ij} \geq De_j} \leq 0 \quad \forall j \quad (2.45)$$

$$\tilde{x}_{ij} \text{ are non - negative fuzzy numbers } \quad \forall i \in S, \forall j \in D \quad (2.46)$$

Step 2: The fuzzy arithmetic operations with requisite constraints in that conjugate model can be performed as follows:

$$\left(\widetilde{Cap}_i * \sum_{j=1}^D \tilde{x}_{ij} \right)_{\sum_j x_{ij} \leq Cap_i}^\alpha = \left\{ Cap_i * \sum_j x_{ij} \mid \langle Cap_i, \sum_j x_{ij} \rangle \in Cap_i^\alpha \times \left[\sum_j x_{ij}, Cap_i \right] \right\} \quad (2.47)$$

$$\left(\widetilde{De}_j * \sum_{i=1}^S \tilde{x}_{ij} \right)_{\sum_i x_{ij} \geq De_j}^\alpha = \left\{ De_j * \sum_i x_{ij} \mid \langle De_j, \sum_i x_{ij} \rangle \in De_j^\alpha \times \left[\overline{De_j}, \sum_i x_{ij} \right] \right\} \quad (2.48)$$

Step 3: Then, we obtain the following final results for these subtraction operations:

$$\left(\widetilde{Cap}_i * \sum_{j=1}^D \tilde{x}_{ij} \right)_{\sum_j x_{ij} \leq Cap_i}^\alpha = \left[0, \overline{Cap_i}(\alpha) - \sum_{j=1}^D x_{ij}(\alpha) \right] \quad (2.49)$$

$$\left(\widetilde{De}_j * \sum_{i=1}^S \tilde{x}_{ij} \right)_{\sum_i x_{ij} \geq De_j}^\alpha = \left[\underline{De_j}(\alpha) - \sum_{i=1}^S x_{ij}(\alpha), 0 \right] \quad (2.50)$$

When the transshipment points on the transportation network are also included, the following results are provided from the fuzzy subtraction operations:

$$\left(\sum_{(i,j) \in A} \tilde{x}_{ij} \ominus \sum_{(j,k) \in A} \tilde{x}_{jk} \right)_{\sum_i x_{ij} = \sum_k x_{jk}}^{\alpha} = \left[\underbrace{\sum_{(i,j) \in A} x_{ij}(\alpha)}_{\underline{\sum_{(i,j) \in A} x_{ij}(\alpha)}} - \underbrace{\sum_{(j,k) \in A} x_{jk}(\alpha)}_{\underline{\sum_{(j,k) \in A} x_{jk}(\alpha)}}, \overline{\sum_{(i,j) \in A} x_{ij}(\alpha)} - \overline{\sum_{(j,k) \in A} x_{jk}(\alpha)} \right] = [0, 0] \quad (2.51)$$

where $j \in T$ is transshipment node, $(i, k) \in A$ represents the set of sources and destinations.

Step 4: Then, this conjugate model can be transformed into the following crisp LP by using the obtained results from the previous step:

$$\text{Minimize} \quad \left[\underline{c}_{ij}(\alpha) \otimes \underline{x}_{ij}(\alpha) + \overline{c}_{ij}(\alpha) \otimes \overline{x}_{ij}(\alpha) \right] \quad (2.52)$$

Subject to:

$$\underline{Cap}_i(\alpha) - \sum_{j=1}^D x_{ij}(\alpha) \geq 0 \quad \forall i \quad (2.53)$$

$$\overline{Cap}_i(\alpha) - \sum_{j=1}^D x_{ij}(\alpha) \geq 0 \quad \forall i \quad (2.54)$$

$$\underline{De}_j(\alpha) - \sum_{i=1}^S x_{ij}(\alpha) \leq 0 \quad \forall j \quad (2.55)$$

$$\overline{De}_j(\alpha) - \sum_{i=1}^S x_{ij}(\alpha) \leq 0 \quad \forall j \quad (2.56)$$

$$\sum_{(i,j) \in A} x_{ij}(\alpha) - \sum_{(j,k) \in A} x_{jk}(\alpha) = 0 \quad \forall j \in T \quad (2.57)$$

$$\sum_{(i,j) \in A} x_{ij}(\alpha) - \sum_{(i,j) \in A} x_{ij}(\alpha) = 0 \quad \forall j \in T \quad (2.58)$$

$$\underline{x}_{ij}(\alpha) \geq 0 \quad \text{and} \quad \overline{x}_{ij}(\alpha) \geq 0 \quad \forall i, \forall j \quad (2.59)$$

Step 5: Substituting the Eq. 2.37 and 2.40 into the above end points, the problem may be written as:

$$\begin{aligned} \text{Min } Z = & \left[\sum_{i=1}^S \sum_{j=1}^D (c_{ij}^p + (c_{ij}^m - c_{ij}^p)\alpha) (x_{ij}^p + (x_{ij}^m - x_{ij}^p)\alpha) \right. \\ & \left. + \sum_{i=1}^S \sum_{j=1}^D (c_{ij}^o - (c_{ij}^o - c_{ij}^m)\alpha) (x_{ij}^o - (x_{ij}^o - x_{ij}^m)\alpha) \right] \end{aligned} \quad (2.60)$$

$$Cap_i^p + (Cap_i^m - Cap_i^p)\alpha - \left(\sum_{j=1}^D x_{ij}^o - \left(\sum_{j=1}^D x_{ij}^o - \sum_{j=1}^D x_{ij}^m \right) \alpha \right) \geq 0 \quad \forall i \quad (2.61)$$

$$Cap_i^o - (Cap_i^o - Cap_i^m)\alpha - \left(\sum_{j=1}^D x_{ij}^p + \left(\sum_{j=1}^D x_{ij}^m - \sum_{j=1}^D x_{ij}^p \right) \alpha \right) \geq 0 \quad \forall i \quad (2.62)$$

$$De_j^p + (De_j^m - De_j^p)\alpha - \left(\sum_{i=1}^S x_{ij}^o - \left(\sum_{i=1}^S x_{ij}^o - \sum_{i=1}^S x_{ij}^m \right) \alpha \right) \leq 0 \quad \forall j \quad (2.63)$$

$$De_j^o - (De_j^o - De_j^m)\alpha - \left(\sum_{i=1}^S x_{ij}^p + \left(\sum_{i=1}^S x_{ij}^m - \sum_{i=1}^S x_{ij}^p \right) \alpha \right) \leq 0 \quad \forall j \quad (2.64)$$

$$\left\{ \sum_{(i,j) \in A} x_{ij}^o - \left(\sum_{(i,j) \in A} x_{ij}^o - \sum_{(i,j) \in A} x_{ij}^m \right) \alpha \right\} - \left\{ \sum_{(j,k) \in A} x_{jk}^o - \left(\sum_{(j,k) \in A} x_{jk}^o - \sum_{(j,k) \in A} x_{jk}^m \right) \alpha \right\} = 0 \quad \forall j \in T \quad (2.65)$$

$$\left\{ \sum_{(i,j) \in A} x_{ij}^p + \left(\sum_{(i,j) \in A} x_{ij}^m - \sum_{(i,j) \in A} x_{ij}^p \right) \alpha \right\} - \left\{ \sum_{(j,k) \in A} x_{jk}^p + \left(\sum_{(j,k) \in A} x_{jk}^m - \sum_{(j,k) \in A} x_{jk}^p \right) \alpha \right\} = 0 \quad \forall j \in T \quad (2.66)$$

$$x_{ij}^o \geq x_{ij}^m, \quad x_{ij}^m \geq x_{ij}^p, \quad x_{ij}^p \geq 0 \quad \forall i, \forall j \quad (2.67)$$

The above crisp equivalent form of the FFTP is provided with α -cut representation as in step 5 by utilizing the CFA approach. However, solution of this crisp LP problem is appropriate only for a risk-averse decision maker. In summary, the total fuzzy transportation cost of the above LP solution can be greater than the existing methods' results as they are not considering decision maker's attitudes toward risk. Moreover, as mentioned at the beginning of this section, risk-averse decision maker may not desire to acquire overly imprecise solutions or overestimation in decision variables. Hence, he/she can obtain crisp and risk-free solution for the FFTP by using the crisp relation while performing the arithmetic operations (Subulan & Baykasoğlu, 2014).

2.5.2 The Proposed Constrained Fuzzy Arithmetic Based Indirect Solution Approach under Fuzzy Equality Constraints

In contrast to risk aversion, the decision maker may be risk-seeker and may has the following vague judgments such as “*transportation quantity from a source should be approximately equal to the capacity of that source*” and “*transportation quantity to a destination should be approximately equal to the demand of that destination*” while solving a FFTP. In this case, it is reasonable to characterize these linguistic expressions by making use of fuzzy relations. These fuzzy equality constraints can be defined by Equations (2.68) to (2.70) for the capacity availability, demand satisfaction and conservation of flow constraints, respectively. Furthermore, the membership functions of these fuzzy constraints can be visualized as in Figures 2.14 to 2.16.

$$\tilde{E}\left(Cap_i, \sum_j x_{ij}\right) = \max\left(0, 1 - \left|Cap_i - \sum_j x_{ij}\right|/\Delta\right) \quad (2.68)$$

$$\tilde{E}\left(De_j, \sum_i x_{ij}\right) = \max\left(0, 1 - \left|De_j - \sum_i x_{ij}\right|/\Delta\right) \quad (2.69)$$

$$\tilde{E}\left(\sum_{(i,j) \in A} x_{ij}, \sum_{(j,k) \in A} x_{jk}\right) = \max\left(0, 1 - \left|\sum_{(i,j) \in A} x_{ij} - \sum_{(j,k) \in A} x_{jk}\right|/\Delta\right) \quad (2.70)$$

where Δ is a positive real number whose value is chosen in each context with aim to make fuzzy relation ($\tilde{E}$) a good representation of the linguistic term “*approximately equal*” in that content.

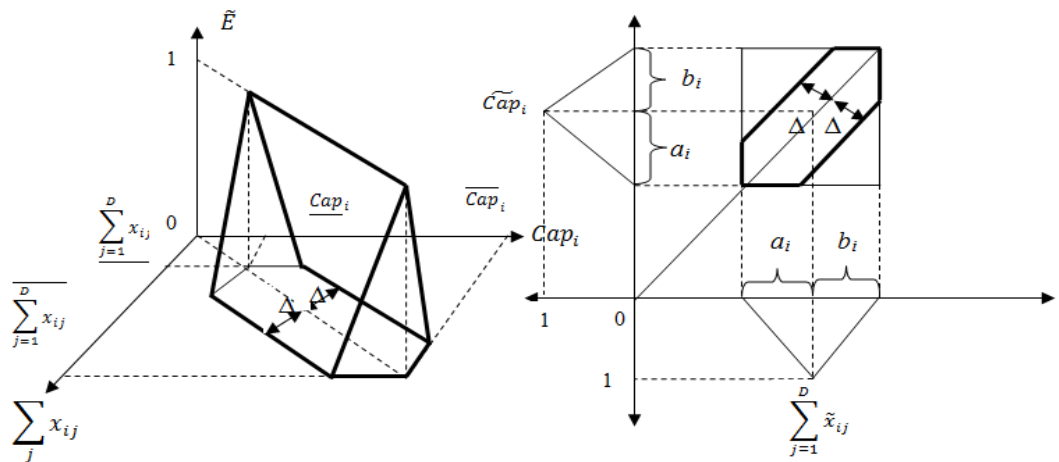


Figure 2.14 Membership function of fuzzy constraint “ $\sum_j x_{ij}$ is approximately equal to Cap_i ”

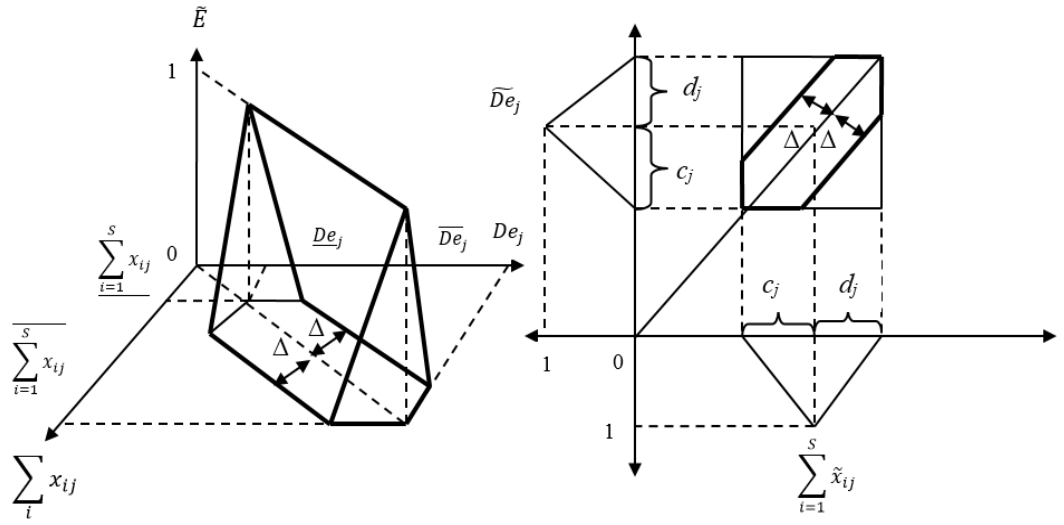


Figure 2.15 Membership function of fuzzy constraint “ $\sum_i x_{ij}$ is approximately equal to De_j ”

The membership function of fuzzy constraint “*approximately equal*” can also be given for the flow balance or conservation of flow constraint at the transshipment points as in Figure 2.16. The proposed CFA based approach is valid for both symmetric and non-symmetric triangular fuzzy numbers. In other words, membership function of the fuzzy relation, “*approximately equal*” has the same form for both symmetric and non-symmetric triangular fuzzy numbers as it is shown in Figure 2.17.

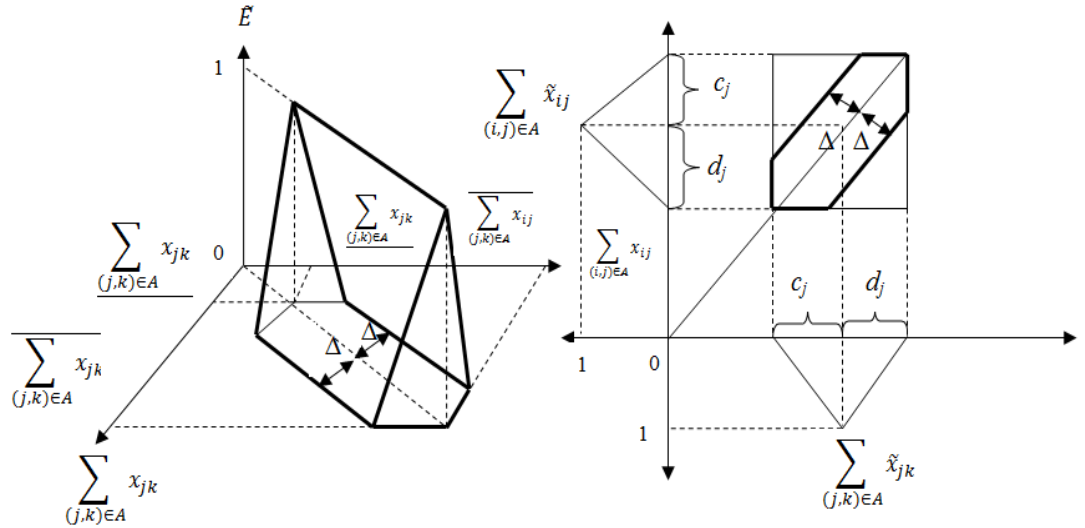


Figure 2.16 Membership function of fuzzy constraint “ $\sum_i x_{ij}$ is approximately equal to $\sum_k x_{jk}$ ”

In fact, core of the membership function regarding this linguistic expression lie down the diagonal of a square which is constituted from the projections of the membership functions corresponding to the examined fuzzy parameters or variables,

$\sum_i x_{ij}$ and De_j . Since structure of the membership functions related to this linguistic expression are similar for both symmetric and non-symmetric triangular fuzzy numbers, type of the utilized triangular fuzzy number is trivial for the proposed approaches (Subulan & Baykasoğlu, 2014). These explanations can be visualized with the aid of points A and B in Figure 2.17.

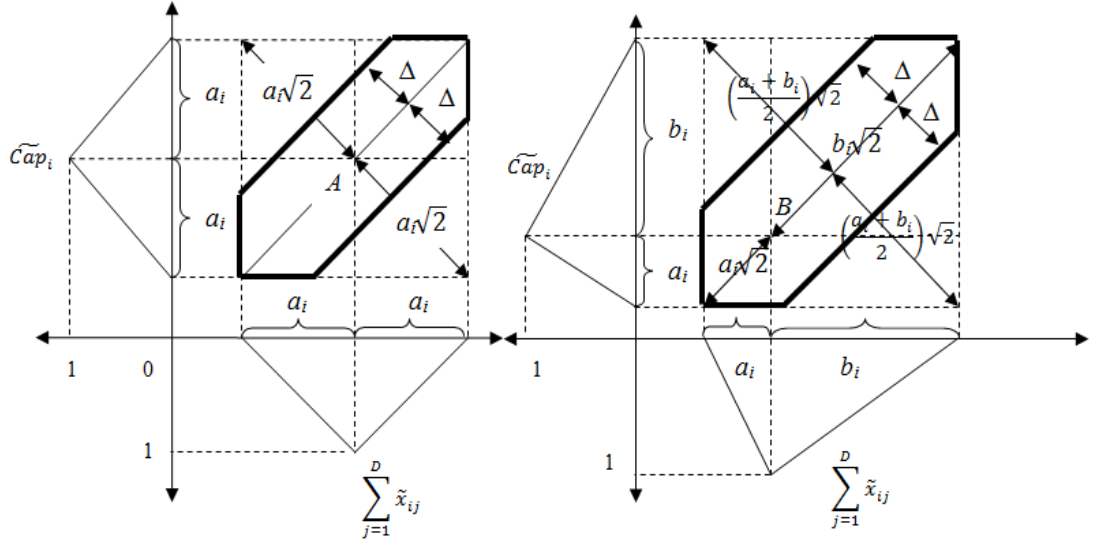


Figure 2.17 Membership function of fuzzy relations for symmetric and non-symmetric fuzzy numbers

In order to obtain realizable solutions for both risk-averse and risk-seekers, some steps (2) - (5) of the proposed CFA based indirect solution approach which are given in Section 2.5.1 should be modified as follows:

Step 2*: The fuzzy arithmetic operations with requisite fuzzy constraints in the conjugate model can be performed as follows:

$$\left(\widetilde{Cap}_i * \sum_{j=1}^D \tilde{x}_{ij} \right)_{\tilde{E}}^{\alpha} = \left\{ Cap_i * \sum_j x_{ij} \mid \langle Cap_i, \sum_j x_{ij} \rangle \in \left(\widetilde{Cap}_i^{\alpha} \times \sum_{j=1}^D \tilde{x}_{ij}^{\alpha} \right) \cap \tilde{E}^{\alpha} \right\} \quad (2.71)$$

$$\left(\widetilde{De}_j * \sum_{i=1}^S \tilde{x}_{ij} \right)_{\tilde{E}}^{\alpha} = \left\{ De_j * \sum_i x_{ij} \mid \langle De_j, \sum_i x_{ij} \rangle \in \left(\widetilde{De}_j^{\alpha} \times \sum_{i=1}^S \tilde{x}_{ij}^{\alpha} \right) \cap \tilde{E}^{\alpha} \right\} \quad (2.72)$$

Step 3*: If all of the uncertain parameters for the given FFTP are symmetric or non-symmetric triangular fuzzy intervals, we can obtain the following results for the subtraction operations under fuzzy relations:

$$\left[\widetilde{Cap}_i \ominus \sum_{j=1}^D \tilde{x}_{ij} \right]_E^\alpha = \left[\underline{Cap}_i(\alpha) - \sum_{j=1}^D \underline{x}_{ij}(\alpha) - \Delta \left(\frac{a_i + b_i}{2} \right) \sqrt{2} (1 - \alpha), \overline{Cap}_i(\alpha) - \sum_{j=1}^D \overline{x}_{ij}(\alpha) + \Delta \left(\frac{a_i + b_i}{2} \right) \sqrt{2} (1 - \alpha) \right]^\alpha \quad (2.73)$$

$$\left[\widetilde{De}_j \ominus \sum_{i=1}^S \tilde{x}_{ij} \right]_{\bar{E}}^\alpha = \left[\underline{De}_j(\alpha) - \sum_{i=1}^S \underline{x}_{ij}(\alpha) - \Delta \left(\frac{c_j + d_j}{2} \right) \sqrt{2} (1 - \alpha), \overline{De}_j(\alpha) - \sum_{i=1}^S \overline{x}_{ij}(\alpha) + \Delta \left(\frac{c_j + d_j}{2} \right) \sqrt{2} (1 - \alpha) \right]^\alpha \quad (2.74)$$

$$\left(\sum_{(i,j) \in A} \tilde{x}_{ij} \ominus \sum_{(j,k) \in A} \tilde{x}_{jk} \right)_{\bar{E}}^\alpha = \left[\sum_{(i,j) \in A} \underline{x}_{ij}(\alpha) - \sum_{(j,k) \in A} \underline{x}_{jk}(\alpha) - \Delta \left(\frac{z_i + t_i}{2} \right) \sqrt{2} (1 - \alpha), \sum_{(j,k) \in A} \overline{x}_{jk}(\alpha) - \sum_{(j,k) \in A} \overline{x}_{jk}(\alpha) + \Delta \left(\frac{z_i + t_i}{2} \right) \sqrt{2} (1 - \alpha) \right]^\alpha \quad (2.75)$$

Step 4*: The crisp equivalent form of the conjugate model can be written as follows by using the results of the fuzzy arithmetic operations obtained from Step-3*:

$$\text{Minimize } \left[\underline{c}_{ij}(\alpha) \otimes \underline{x}_{ij}(\alpha) + \overline{c}_{ij}(\alpha) \otimes \overline{x}_{ij}(\alpha) \right] \quad (2.76)$$

Subject to:

$$\underline{Cap}_i(\alpha) - \sum_{j=1}^D \underline{x}_{ij}(\alpha) \geq -\Delta \sqrt{2} \left(\frac{\overline{Cap}_i(\alpha) - \underline{Cap}_i(\alpha)}{2} \right) \quad \forall i \quad (2.77)$$

$$\overline{Cap}_i(\alpha) - \sum_{j=1}^D \overline{x}_{ij}(\alpha) \geq \Delta \sqrt{2} \left(\frac{\overline{Cap}_i(\alpha) - \underline{Cap}_i(\alpha)}{2} \right) \quad \forall i \quad (2.78)$$

$$\underline{De}_j(\alpha) - \sum_{i=1}^S \underline{x}_{ij}(\alpha) \leq -\Delta \sqrt{2} \left(\frac{\overline{De}_j(\alpha) - \underline{De}_j(\alpha)}{2} \right) \quad \forall j \quad (2.79)$$

$$\overline{De_j}(\alpha) - \sum_{i=1}^S x_{ij}(\alpha) \leq \Delta\sqrt{2} \left(\frac{\overline{De_j}(\alpha) - \underline{De_j}(\alpha)}{2} \right) \quad \forall j \quad (2.80)$$

The following constraints are required in case of fully fuzzy transshipment case.

$$\sum_{(i,j) \in A} x_{ij}(\alpha) - \sum_{(j,k) \in A} x_{jk}(\alpha) = -\Delta\sqrt{2} \cdot \left(\frac{\sum_{(i,j) \in A} \overline{x_{ij}(\alpha)} - \sum_{(j,k) \in A} \overline{x_{jk}(\alpha)}}{2} \right) \quad \forall j \in T \quad (2.81)$$

$$\sum_{(i,j) \in A} \overline{x_{ij}(\alpha)} - \sum_{(j,k) \in A} \overline{x_{jk}(\alpha)} = \Delta\sqrt{2} \cdot \left(\frac{\sum_{(i,j) \in A} \overline{x_{ij}(\alpha)} - \sum_{(j,k) \in A} \overline{x_{jk}(\alpha)}}{2} \right) \quad \forall j \in T \quad (2.82)$$

$$\underline{x_{ij}(\alpha)} \geq 0, \overline{x_{ij}(\alpha)} \geq 0, \overline{x_{jk}(\alpha)} \geq 0 \quad \text{and} \quad \underline{x_{jk}(\alpha)} \geq 0 \quad \forall i, \forall j, \forall k \quad (2.83)$$

These constraints involved the above step can also be presented in a more compact manner by using the widths of the triangular fuzzy numbers as follows:

$$\underline{Cap_i}(\alpha) - \sum_{j=1}^D x_{ij}(\alpha) \geq -\Delta \left(\frac{a_i + b_i}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall i \quad (2.84)$$

$$\overline{Cap_i}(\alpha) - \sum_{j=1}^D x_{ij}(\alpha) \geq \Delta \left(\frac{a_i + b_i}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall i \quad (2.85)$$

$$\underline{De_j}(\alpha) - \sum_{i=1}^S x_{ij}(\alpha) \leq -\Delta \left(\frac{c_j + d_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \quad (2.86)$$

$$\overline{De_j}(\alpha) - \sum_{i=1}^S x_{ij}(\alpha) \leq \Delta \left(\frac{c_j + d_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \quad (2.87)$$

$$\sum_{(i,j) \in A} x_{ij}(\alpha) - \sum_{(j,k) \in A} x_{jk}(\alpha) = -\Delta \left(\frac{z_j + t_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \in T \quad (2.88)$$

$$\sum_{(i,j) \in A} \overline{x_{ij}(\alpha)} - \sum_{(j,k) \in A} \overline{x_{jk}(\alpha)} = \Delta \left(\frac{z_j + t_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \in T \quad (2.89)$$

$$\underline{x_{ij}(\alpha)} \geq 0, \overline{x_{ij}(\alpha)} \geq 0, \overline{x_{jk}(\alpha)} \geq 0 \quad \text{and} \quad \underline{x_{jk}(\alpha)} \geq 0 \quad \forall i, \forall j, \forall k \quad (2.90)$$

Step 5*: Substituting the Equations (2.37) and (2.40) into the above end points, the crisp LP problem may also be written as:

$$\begin{aligned} \text{Min } Z = & \left[\sum_{i=1}^S \sum_{j=1}^D (c_{ij}^p + (c_{ij}^m - c_{ij}^p)\alpha)(x_{ij}^p + (x_{ij}^m - x_{ij}^p)\alpha) \right. \\ & \left. + \sum_{i=1}^S \sum_{j=1}^D (c_{ij}^o - (c_{ij}^o - c_{ij}^m)\alpha)(x_{ij}^o - (x_{ij}^o - x_{ij}^m)\alpha) \right] \end{aligned} \quad (2.91)$$

$$Cap_i^p + (Cap_i^m - Cap_i^p)\alpha - \left(\sum_{j=1}^D x_{ij}^o - \left(\sum_{j=1}^D x_{ij}^o - \sum_{j=1}^D x_{ij}^m \right) \alpha \right) \geq -\Delta \left(\frac{a_i + b_i}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall i \quad (2.92)$$

$$Cap_i^o - (Cap_i^o - Cap_i^m)\alpha - \left(\sum_{j=1}^D x_{ij}^p + \left(\sum_{j=1}^D x_{ij}^m - \sum_{j=1}^D x_{ij}^p \right) \alpha \right) \geq \Delta \left(\frac{a_i + b_i}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall i \quad (2.93)$$

$$De_j^p + (De_j^m - De_j^p)\alpha - \left(\sum_{i=1}^S x_{ij}^o - \left(\sum_{i=1}^S x_{ij}^o - \sum_{i=1}^S x_{ij}^m \right) \alpha \right) \leq -\Delta \left(\frac{c_j + d_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \quad (2.94)$$

$$De_j^o - (De_j^o - De_j^m)\alpha - \left(\sum_{i=1}^S x_{ij}^p + \left(\sum_{i=1}^S x_{ij}^m - \sum_{i=1}^S x_{ij}^p \right) \alpha \right) \leq \Delta \left(\frac{c_j + d_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \quad (2.95)$$

$$\begin{aligned} & \left\{ \sum_{(i,j) \in A} x_{ij}^p + \left(\sum_{(i,j) \in A} x_{ij}^m - \sum_{(i,j) \in A} x_{ij}^p \right) \alpha \right\} - \left\{ \sum_{(j,k) \in A} x_{jk}^o - \left(\sum_{(j,k) \in A} x_{jk}^o - \sum_{(j,k) \in A} x_{jk}^m \right) \alpha \right\} \\ & = -\Delta \left(\frac{z_j + t_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \in T \end{aligned} \quad (2.96)$$

$$\begin{aligned} & \left\{ \sum_{(i,j) \in A} x_{ij}^o - \left(\sum_{(i,j) \in A} x_{ij}^o - \sum_{(i,j) \in A} x_{ij}^m \right) \alpha \right\} - \left\{ \sum_{(j,k) \in A} x_{jk}^p + \left(\sum_{(j,k) \in A} x_{jk}^m - \sum_{(j,k) \in A} x_{jk}^p \right) \alpha \right\} \\ & = \Delta \left(\frac{z_j + t_j}{2} \right) \sqrt{2}(1 - \alpha) \quad \forall j \in T \end{aligned} \quad (2.97)$$

$$x_{ij}^o \geq x_{ij}^m, \quad x_{ij}^m \geq x_{ij}^p, \quad x_{ij}^p \geq 0, \quad x_{jk}^o \geq x_{jk}^m, \quad x_{jk}^m \geq x_{jk}^p, \quad x_{jk}^p \geq 0 \quad \forall i, \forall j, \forall k \quad (2.98)$$

The value of parameter, Δ which is related to fuzzy relation may change according to decision maker's attitude toward risk. For instance, when Δ is equal to zero, the proposed approach will be more appropriate for a risk-averse person. On the other hand, when the value of this parameter is equal to $\sqrt{2}$, it is more suitable for a risk seeker. For this reason, the proposed approach will not present only the most risky solution as in the existing methods in the literature but also risk-free solutions according to risk attitude of the decision maker. Thus, more reliable solutions can be obtained by utilizing this approach. Furthermore, this approach assists decision maker with yielding fuzzy efficient solutions under different uncertainty levels (α -cuts).

2.6 The Proposed Direct Solution Approach Based on Constrained Fuzzy Arithmetic Concept and Particle Swarm Optimization Algorithm

In this section, a new CFA based fuzzy decoding procedure is presented for direct solution of FFTP with fuzzy decision variables. The proposed fuzzy decoding procedure also incorporates a defuzzification technique and priority-based encoding method for solution representation of transportation networks. In the proposed fuzzy decoding procedure, a defuzzification technique and α -cuts are used. The defuzzification technique is utilized to rank fuzzy fitness function values and compare the fuzzy transportation cost parameters. In order to generate new solution vectors and to provide fuzzy efficient solutions, the proposed fuzzy decoding procedure is incorporated into a meta-heuristic algorithm namely PSO. The proposed direct solution approach can be divided into three parts including CFA operations within the decoding procedure, encoding with fuzzy decoding procedure and the PSO algorithm (Baykasoğlu & Subulan, 2015). Since the CFA operations are elaborated into the former sections, they are not discussed one more time in this section.

2.6.1 Priority Based Encoding and Proposed Fuzzy Decoding Procedure

Before implementation steps of the utilized metaheuristic algorithm, i.e., PSO which is incorporated into the proposed direct solution approach, solution representation for the examined FFTP is needed. It should be noted here that selection of the appropriate solution representation may affect the performance of the proposed direct solution approach. In fact, among the several encoding methods, i.e. matrix encoding, spanning tree method etc. for solution representation of network problems, priority-based encoding method is utilized in this section. Because, this method does not need to use an additional repair mechanism and reduce the chromosome dimension (Gen & Cheng, 1997; Gen & Cheng, 2000). However, this method requires a decoding procedure for constructing the entire solution. In addition, the continuous nature of the PSO algorithm avoids the direct application of this meta-heuristic to discrete combinatorial optimization problems. For this reason, largest-value-order (LOV) based on random key representation is used in order to transform the continuous solution vector to discrete node permutation (sources/destinations). In detail, random key technique encodes a solution with random numbers and these numbers are used as

sort keys while decoding the solution. Moreover, the solution vector is divided into two segments for the sources and destinations, respectively. For a better understanding of overall encoded solution, a priority-based encoding for a balanced transportation tree with three sources and four destinations is displayed in Figure 2.18. The corresponding fuzzy transportation cost matrix is also presented in the same figure.

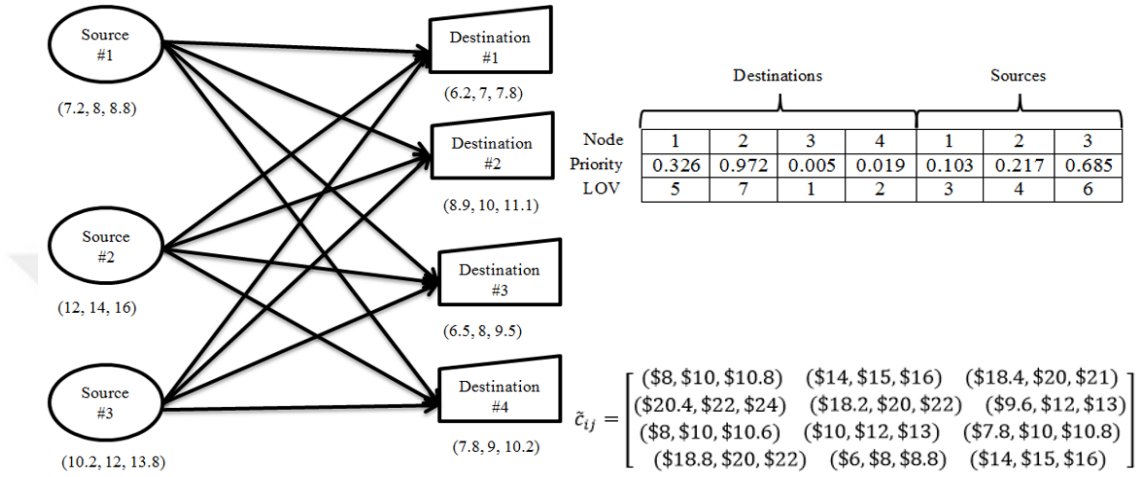


Figure 2.18 An illustrative priority-based encoding for a balanced transportation tree

The pseudo code of the proposed fuzzy decoding procedure for a FFTP is shown in Table 2.2. In fact, the proposed decoding procedure mainly depends on the priority-based encoding which was firstly developed by (Gen & Cheng, 2000). Apart from the existing literature (Gen et al., 2006; Altiparmak et al., 2006; Altiparmak et al., 2009; Pishvae et al., 2010; Subulan et al., 2014) in which the crisp version of a decoding procedure is applied for transportation networks, arithmetic operations are performed on triangular fuzzy numbers instead of crisp real numbers. Actually, the available literature only reflects the crisp version of the decoding procedure for solving the supply chain planning problems by separating into several transportation problems. In this section, fuzzy numbers are assigned to transportation quantities which correspond to the decision variables of the transportation problem (Baykasoğlu & Subulan, 2015). Additionally, CFA operations are utilized while calculating the remaining capacities of the sources and remaining demands of the destinations. In fact, while performing fuzzy subtraction operations and assigning the fuzzy transportation amounts, CFA concept with crisp and/or fuzzy relations are implemented.

Table 2.2 The pseudo code of the proposed CFA based decoding procedure for direct solution of FFTPs (Baykasoğlu & Subulan, 2015)

1:	// Procedure: Pseudo code of the proposed CFA based decoding algorithm for priority-based encoding of a fully fuzzy transportation network
2:	Inputs: S : set of sources, D : set of destinations, $\bar{D}_{e_j}$: fuzzy demand of destination j , $\bar{C}ap_i$: fuzzy capacity of source i , $\bar{c}_{ij}$: fuzzy unit transportation cost from source node i to destination node j , M is positive huge number
	α -cuts of fuzzy numbers $\alpha \in [0,1]$, λ index of optimism for decision maker $\lambda \in [0,1]$, Δ a positive real number for representation of linguistic term "approximately equal" $\Delta \in [0, \sqrt{2}]$, $v(j+i)$: encoded solution (chromosome)
3:	Outputs: $\bar{x}_{ij}$: fuzzy transportation quantity shipped to destination j from source i
If	$\sum_{i=1}^S \bar{C}ap_i = \sum_{j=1}^D \bar{D}_{e_j}$, Then balanced fully fuzzy transportation problem or If $\sum_{i=1}^S \bar{C}ap_i \approx \sum_{j=1}^D \bar{D}_{e_j}$, Then unbalanced fully fuzzy transportation problem
4:	// Defuzzification of the unit transportation costs by using method [30] and assignment of initial values to fuzzy transportation quantities (Step-1)
5:	$(c_{ij}^\alpha)^\lambda = [\lambda \cdot c_{ij}(\alpha) + (1-\lambda) \cdot \bar{c}_{ij}(\alpha)]$ and $\bar{x}_{ij} = (0, 0, 0) \forall i, \forall j$
6:	For each particle in the swarm Do // Decoding of each chromosome into the swarm
7:	While $v(j+i) \neq -99999$ (any huge negative number, Select a node based on $\pi = \text{argmax}\{v(t), t \in D + S \} \forall i \in S, \forall j \in D$ // Selection of a node on the transportation network based on LOV (Step-2)
8:	If $\pi \in D$ then a destination point is selected $j^* = \pi$, Then $i^* = \text{argmin}\{(c_{ij}^\alpha)^\lambda \mid v(i) \neq -99999 \ i \in S\}$ // Select a source with the lowest transportation cost and no empty capacity (Step-3)
9:	If Length of $i^* > 1$ (two sources with equal defuzzified transportation cost), Then select one of them randomly // Step-4
10:	end if
11:	Else $\pi \in S$ then a source is selected $i^* = \pi$, $j^* = \text{argmin}\{(c_{ij}^\alpha)^\lambda \mid v(j) \neq -99999 \ j \in D\}$ // Select a destination with the lowest transportation cost and no empty demand (Step-3)
12:	If Length of $j^* > 1$ (two destinations with equal defuzzified transportation cost), Then select one of them randomly // Step-4
13:	end if
14:	If $\bar{C}ap_{i^*}(\alpha) - \bar{D}_{e_{j^*}}(\alpha) - \Delta\sqrt{2} \left(\frac{\bar{D}_{e_j}(\alpha) - \underline{D}_{e_j}(\alpha)}{2} \right) \geq -\Delta\sqrt{2} \left(\frac{\bar{C}ap_i(\alpha) - \underline{C}ap_i(\alpha)}{2} \right)$ and $\bar{C}ap_{i^*}(\alpha) - \underline{D}_{e_{j^*}}(\alpha) \geq \Delta\sqrt{2} \left(\frac{\bar{C}ap_i(\alpha) - \underline{C}ap_i(\alpha)}{2} \right)$ // Capacity control check for assigning transport quantity as fuzzy demands (Step-5)
15:	$\underline{x}_{i^*j^*}(\alpha) = \underline{D}_{e_{j^*}}(\alpha)$ and $\bar{x}_{i^*j^*}(\alpha) = \bar{D}_{e_{j^*}}(\alpha)$
16:	If $\bar{D}_{e_j}(\alpha) - \bar{x}_{i^*j^*}(\alpha) \leq -\Delta\sqrt{2} \left(\frac{\bar{D}_{e_j}(\alpha) - \underline{D}_{e_j}(\alpha)}{2} \right)$ and $\bar{D}_{e_j}(\alpha) - \underline{x}_{i^*j^*}(\alpha) \leq \Delta\sqrt{2} \left(\frac{\bar{D}_{e_j}(\alpha) - \underline{D}_{e_j}(\alpha)}{2} \right)$, Then $\underline{x}_{i^*j^*}(\alpha) = \underline{D}_{e_{j^*}}(\alpha)$ and $\bar{x}_{i^*j^*}(\alpha) = \bar{D}_{e_{j^*}}(\alpha)$ // Determining the fuzzy transportation quantity
17:	$\underline{D}_{e_{j^*}}(\alpha) = \underline{D}_{e_{j^*}}(\alpha) - \bar{x}_{i^*j^*}(\alpha)$ and $\bar{D}_{e_{j^*}}(\alpha) = \bar{D}_{e_{j^*}}(\alpha) - \underline{x}_{i^*j^*}(\alpha)$, $v(j^*) = -99999$ and $(c_{ij^*}^\alpha)^\lambda = M$ // Update the remaining fuzzy demand of destination and transportation matrix
18:	Else $\underline{x}_{i^*j^*}(\alpha) = \bar{D}_{e_{j^*}}(\alpha) - \Delta\sqrt{2} \left(\frac{\bar{D}_{e_j}(\alpha) - \underline{D}_{e_j}(\alpha)}{2} \right)$ and $\bar{x}_{i^*j^*}(\alpha) = \underline{D}_{e_{j^*}}(\alpha) + \Delta\sqrt{2} \left(\frac{\bar{D}_{e_j}(\alpha) - \underline{D}_{e_j}(\alpha)}{2} \right)$ // Determine fuzzy transportation quantity
19:	If $\bar{x}_{i^*j^*}(\alpha) < \underline{x}_{i^*j^*}(\alpha)$, Then $\bar{x}_{i^*j^*}(\alpha) = \underline{x}_{i^*j^*}(\alpha)$ // Logical check on fuzzy transportation quantity
20:	end if
21:	$\underline{D}_{e_{j^*}}(\alpha) = \underline{D}_{e_{j^*}}(\alpha) - \bar{x}_{i^*j^*}(\alpha)$ and $\bar{D}_{e_{j^*}}(\alpha) = \bar{D}_{e_{j^*}}(\alpha) - \underline{x}_{i^*j^*}(\alpha)$, $v(j^*) = -99999$ and $(c_{ij^*}^\alpha)^\lambda = M$ // Update the remaining fuzzy demand of destination and transportation matrix
22:	$\underline{C}ap_{i^*}(\alpha) = \underline{C}ap_{i^*}(\alpha) - \bar{x}_{i^*j^*}(\alpha)$ and $\bar{C}ap_{i^*}(\alpha) = \bar{C}ap_{i^*}(\alpha) - \underline{x}_{i^*j^*}(\alpha)$ // Update the remaining fuzzy capacity of the source
23:	Else $\underline{x}_{i^*j^*}(\alpha) = \bar{C}ap_{i^*}(\alpha) - \Delta\sqrt{2} \left(\frac{\bar{C}ap_i(\alpha) - \underline{C}ap_i(\alpha)}{2} \right)$ and $\bar{x}_{i^*j^*}(\alpha) = \underline{C}ap_{i^*}(\alpha) + \Delta\sqrt{2} \left(\frac{\bar{C}ap_i(\alpha) - \underline{C}ap_i(\alpha)}{2} \right)$ // Determine fuzzy transportation quantity as the fuzzy remaining capacity of the selected source
24:	If $\bar{D}_{e_j}(\alpha) - \bar{x}_{i^*j^*}(\alpha) \geq -\Delta\sqrt{2} \left(\frac{\bar{D}_{e_j}(\alpha) - \underline{D}_{e_j}(\alpha)}{2} \right)$ and $\bar{D}_{e_j}(\alpha) - \underline{x}_{i^*j^*}(\alpha) \geq \Delta\sqrt{2} \left(\frac{\bar{D}_{e_j}(\alpha) - \underline{D}_{e_j}(\alpha)}{2} \right)$
25:	$\underline{x}_{i^*j^*}(\alpha) = \bar{C}ap_{i^*}(\alpha) - \Delta\sqrt{2} \left(\frac{\bar{C}ap_i(\alpha) - \underline{C}ap_i(\alpha)}{2} \right)$ and $\bar{x}_{i^*j^*}(\alpha) = \underline{C}ap_{i^*}(\alpha) + \Delta\sqrt{2} \left(\frac{\bar{C}ap_i(\alpha) - \underline{C}ap_i(\alpha)}{2} \right)$ // Determine fuzzy transportation quantity

Table 2.2 The pseudo code of the proposed CFA based decoding procedure for direct solution of FFTPs (Continued)

26:	Else if $\overline{De}_j(\alpha) - \underline{x}_{i^*j^*}(\alpha) \geq \Delta\sqrt{2} \left(\frac{\overline{De}_j(\alpha) - \underline{De}_j(\alpha)}{2} \right)$, Then $\underline{x}_{i^*j^*}(\alpha) = \overline{Cap}_{i^*}(\alpha) - \Delta\sqrt{2} \left(\frac{\overline{Cap}_{i^*}(\alpha) - \underline{Cap}_{i^*}(\alpha)}{2} \right)$
27:	end Else if
28:	If $\underline{De}_j(\alpha) - \overline{x}_{i^*j^*}(\alpha) \geq -\Delta\sqrt{2} \left(\frac{\overline{De}_j(\alpha) - \underline{De}_j(\alpha)}{2} \right)$, Then $\overline{x}_{i^*j^*}(\alpha) = \left \underline{Cap}_{i^*}(\alpha) + \Delta\sqrt{2} \left(\frac{\overline{De}_j(\alpha) - \underline{De}_j(\alpha)}{2} \right) \right $
29:	Else $\overline{x}_{i^*j^*}(\alpha) = \underline{x}_{i^*j^*}(\alpha) + 2 \cdot \left(\overline{De}_j(\alpha) - \underline{x}_{i^*j^*}(\alpha) - \Delta\sqrt{2} \left(\frac{\overline{De}_j(\alpha) - \underline{De}_j(\alpha)}{2} \right) \right)$
30:	End if
31:	End if
32:	If $\overline{x}_{i^*j^*}(\alpha) < \underline{x}_{i^*j^*}(\alpha)$, Then $\underline{x}_{i^*j^*}(\alpha) = \overline{x}_{i^*j^*}(\alpha)$ // Logical check on fuzzy transportation quantity
33:	End if
34:	If $\underline{x}_{i^*j^*}(\alpha) < 0$, Then $\underline{x}_{i^*j^*}(\alpha) = 0$ // Non-negativity condition for fuzzy decision variables
35:	End if
36:	$\underline{De}_{j^*}(\alpha) = \underline{De}_j(\alpha) - \overline{x}_{i^*j^*}(\alpha)$ and $\overline{De}_{j^*}(\alpha) = \overline{De}_j(\alpha) - \underline{x}_{i^*j^*}(\alpha)$ // Update the remaining fuzzy demand of destination
37:	$\underline{Cap}_{i^*}(\alpha) = \underline{Cap}_i(\alpha) - \overline{x}_{i^*j^*}(\alpha)$ and $\overline{Cap}_{i^*}(\alpha) = \overline{Cap}_i(\alpha) - \underline{x}_{i^*j^*}(\alpha)$, $(c_{i^*j^*}^\alpha)^\lambda = M$ // Update the remaining fuzzy capacity of the source and transportation matrix (Step-6)
38:	End if
39:	If $\underline{De}_{j^*}(\alpha) \leq -\Delta\sqrt{2} \left(\frac{\overline{De}_{j^*}(\alpha) - \underline{De}_{j^*}(\alpha)}{2} \right)$ and $\overline{De}_{j^*}(\alpha) \leq \Delta\sqrt{2} \left(\frac{\overline{De}_{j^*}(\alpha) - \underline{De}_{j^*}(\alpha)}{2} \right)$, Then $v(j^*) = -99999$ and $(c_{i^*j^*}^\alpha)^\lambda = M$ // Update the selected destination value on chromosome and transportation matrix
40:	End if
41:	If $\underline{Cap}_{i^*}(\alpha) \leq -\Delta\sqrt{2} \left(\frac{\overline{Cap}_{i^*}(\alpha) - \underline{Cap}_{i^*}(\alpha)}{2} \right)$ and $\overline{Cap}_{i^*}(\alpha) \leq \Delta\sqrt{2} \left(\frac{\overline{Cap}_{i^*}(\alpha) - \underline{Cap}_{i^*}(\alpha)}{2} \right)$, Then $v(i^*) = -99999$ and $(c_{i^*j^*}^\alpha)^\lambda = M$ // Update the selected source on chromosome and transportation matrix
42:	End if
43:	Calculate $Dist = \min(c_{i^*j^*}^\alpha)$ for the selected source, i^* // Removing the source (with a positive fuzzy remaining capacity but maximal transportation cost) from the chromosome
44:	If $Dist = M$, Then $v(i^*) = -99999$
45:	End if
46:	End if
47:	Calculate $\underline{\Phi} = \sum_{i=1}^S \sum_{j=1}^D \underline{x}_{ij}(\alpha)$ and $\overline{\Phi} = \sum_{i=1}^S \sum_{j=1}^D \overline{x}_{ij}(\alpha)$ // Control of the fuzzy demand satisfaction of the destinations (Step-7)
48:	If $\underline{\Phi} = \sum_{j=1}^D \underline{De}_j(\alpha) \leq \sum_{i=1}^S \underline{Cap}_i(\alpha)$ and $\overline{\Phi} = \sum_{j=1}^D \overline{De}_j(\alpha) \leq \sum_{i=1}^S \overline{Cap}_i(\alpha)$
49:	Find $\{i^{**} \in S \mid \underline{Cap}_{i^{**}}(\alpha) > 0 \text{ or } \overline{Cap}_{i^{**}}(\alpha) > 0\}$, Then $v(i^*) = -99999$, $v(j + i) = -99999 \quad \forall i \in S, \forall j \in D$ // Removing the sources (with positive fuzzy remaining capacity) from the chromosome (Step-8)
50:	End if
51:	End while
52:	Calculate the fuzzy fitness function value $\left[\sum_{i=1}^S \sum_{j=1}^D \underline{c}_{ij}(\alpha) \otimes \underline{x}_{ij}(\alpha), \sum_{i=1}^S \sum_{j=1}^D \overline{c}_{ij}(\alpha) \otimes \overline{x}_{ij}(\alpha) \right]$ // Calculation of the fuzzy total transportation cost value (Step-9)
53:	End for

Moreover, a defuzzification technique which was developed by Hus and Nian (1997) is used to rank fuzzy fitness function values and to compare the fuzzy transportation costs given in Figure 2.18. Therefore, the proposed decoding procedure presents fuzzy version of decoding procedures available in the literature. In contrast to the available crisp versions, we also designed the fuzzy version of the decoding algorithm for balancing the unbalanced FFTPs without adding any dummy destination node. Furthermore, the proposed fuzzy decoding procedure takes into account the approximately equal fuzzy transportation cost values. The decoding procedure is reiterated until all of the fuzzy demands of the destinations are satisfied by the sources with fuzzy capacities. Differently from the existing crisp version of the decoding algorithm, a very big negative value (-99999) is assigned to the leaving nodes (sources with empty capacity or destinations with no demand) since the continuous nature of the used meta-heuristic algorithm, i.e., PSO (Subulan et al., 2014). In order to clarify the mechanism of the proposed fuzzy decoding procedure, the trace table for the sample solution vector which is given in Figure 2.18 is shown in the following Table 2.3. Actually, this table presents a fuzzy efficient solution for the balanced transportation case and the decision maker is assumed to be a risk seeker ($\Delta = \sqrt{2}$). Additionally, this solution is provided when the α -cut level is set to zero. Moreover, the trace tables for the unbalanced transportation case are also presented for a risk-seeker and partially risk-averse person ($\Delta = 0.35$) in Tables 2.4 and 2.5, respectively. In these tables, different solution vectors are used in order to show the different cases encountered in the decoding phase and obtain different kinds of fuzzy solutions. It should be noted here that different chromosomes may require different total number of iterations in the decoding phase while constructing the entire fuzzy solution.

Table 2.3 Trace table for encoding of balanced case with sample chromosome ($\alpha = 0$, $\Delta = \sqrt{2}$)

Iter.	$v(j+t)$ solution vector	$\widetilde{Cap}_i$	$\widetilde{De}_j$	LOV	j	i	$\widetilde{x}_{ij}$
1	(0.326 0.972 0.005 0.019 0.103 0.217 0.685)	(10.2, 12, 13.8)	(8.9, 10, 11.1)	D2	D2	S3	[8.9, 11.1]
2	(0.326 -99999 0.005 0.019 0.103 0.217 0.685)	[-0.9, 4.9] NA	(6.5, 8, 9.5) [3.8, 8.2]	S3	D3	S3	[1.3, 2.7]
3	(0.326 -99999 0.005 0.019 0.103 0.217 -99999)	(7.2, 8, 8.8) [-0.6, 2.6]	(6.2, 7, 7.8) NA	D1	D1	S1	[6.2, 7.8]
4	(-99999 -99999 0.005 0.019 0.103 0.217 -99999)	(12, 14, 16) [1.8, 8.2]	(7.8, 9, 10.2) NA	S2	D4	S2	[7.8, 10.2]
5	(-99999 -99999 0.005 -99999 0.103 0.217 -99999)	[1.8, 8.2] NA	[3.8, 8.2] [-2, 4]	S2	D3	S2	[4.2, 5.8]
6	(-99999 -99999 0.005 -99999 0.103 -99999 -99999)	[-0.6, 2.6] NA	[-2, 4] NA	S1	D3	S1	[1, 1]
7	(-99999 -99999 -99999 -99999 -99999 -99999 -99999)	-	-	-	-	-	-

Table 2.4 Trace table for encoding procedure of unbalanced FFTP case ($\alpha = 0$, $\Delta = \sqrt{2}$)

Iter.	$v(j+i)$ solution vector	$\widehat{Cap}_i$	$\widehat{De}_j$	LOV	j	i	$\tilde{x}_{ij}$
1	(0.725 0.387 0.423 0.515 0.215 0.108 0.04)	(550, 650, 800) [200, 550]	(250, 300, 350) NA	D1	D1	S1	[250, 350]
2	(-99999 0.387 0.423 0.515 0.215 0.108 0.04)	(550, 700, 850) [150, 550]	(300, 350, 400) NA	D4	D4	S2	[300, 400]
3	(-99999 0.387 0.423 -99999 0.215 0.108 0.04)	[200, 550] [-150, 300]	(250, 300, 350) NA	D3	D3	S1	[250, 350]
4	(-99999 0.387 -99999 -99999 0.215 0.108 0.04)	[150, 550] [-200, 300]	(300, 350, 400) [-50, 150]	D2	D2	S2	[250, 350]
5	(-99999 0.387 -99999 -99999 0.215 0.108 0.04)	[-150, 300] [-200, 250]	[-50, 150] NA	D2	D2	S1	[50, 50]
6	(-99999 -99999 -99999 -99999 0.215 0.108 0.04)	NA	NA	-	-	-	-
7	(-99999 -99999 -99999 -99999 -99999 -99999 -99999)	-	-	-	-	-	-

Table 2.5 Trace table for encoding procedure of unbalanced FFTP case ($\alpha = 0$, $\Delta = 0.35$)

Iter.	$v(j+i)$ solution vector	$\widehat{Cap}_i$	$\widehat{De}_j$	LOV	j	i	$\tilde{x}_{ij}$
1	(0.387 0.215 0.725 0.515 0.108 0.423 0.04)	(550, 650, 800) [224.7, 474.7]	(250, 300, 350) NA	D3	D3	S1	[325.25, 325.25]
2	(0.387 0.215 -99999 0.515 0.108 0.423 0.04)	(550, 700, 850) [174.7, 474.7]	(300, 350, 400) NA	D4	D4	S2	[375.25, 375.25]
3	(0.387 0.215 -99999 -9999 0.108 0.423 0.04)	[174.7, 474.7] [-74.2, 225.8]	(300, 350, 400) [51, 151]	S2	D2	S2	[248.99, 248.99]
4	(0.387 0.215 -99999 -9999 0.108 -99999 0.04)	[-74.2, 225.8] [-74.2, 225.8]	(250, 300, 350) [250, 350]	S2	D1	S2	[0, 0]
5	(0.387 0.215 -99999 -9999 0.108 -99999 0.04)	[224.7, 474.7] [-61.9, 188.1]	(250, 300, 350) [-36.62, 63.37]	D1	D1	S1	[286.62, 286.62]
6	(-99999 0.215 -99999 -9999 0.108 -99999 0.04)	(600, 800, 1000) [561.36, 961.36]	[-36.62, 63.37] NA	D1	D1	S3	[38.63, 38.63]
7	(-99999 0.215 -99999 -9999 0.108 -99999 0.04)	[-61.9, 188.1] [-61.9, 188.1]	[51, 151] [51, 151]	D2	D2	S1	[0, 0]
8	(-99999 -99999 -99999 -9999 0.108 -99999 0.04)	[561.36, 961.36] [435.11, 835.11]	[51, 151] NA	D2	D2	S3	[126.25, 126.25]
9	(-99999 -99999 -99999 -99999 0.108 -99999 0.04)	NA	NA	-	-	-	-
10	(-99999 -99999 -99999 -99999 -99999 -99999 -99999)	-	-	-	-	-	-

2.6.2 Particle Swarm Optimization (PSO) Algorithm

PSO is one of the well-known and accepted population-based evolutionary computation technique that was developed by Eberhart and Kennedy (1995) inspired from the social behavior of bird flocks and fish schools (swarms) searching for food. In fact, it is a robust stochastic optimization technique for solving continuous non-linear function optimization. In this algorithm, each individual represents a particle and each particle flies around in the multi-dimensional search space with a velocity that is constantly changed according to the particle's own experience and experience of the whole swarm. This algorithm differentiates from the traditional evolutionary algorithms in a way that any filtering operation such as crossover or mutation was not utilized for generating new solutions. Furthermore, in order to reach the best position, the obtained information so far are socially shared among the particles (Tasgetiren et al., 2007). In this section, we adopted global best PSO algorithm for direct solution of

balanced/unbalanced FFTP's by incorporating the proposed CFA based decoding procedure and a fuzzy ranking function into this procedure. The main implementation steps of the global best PSO algorithm can be summarized by the following pseudo code given in Table 2.6.

Table 2.6 The pseudo code of global best PSO algorithm

```

1: // Determine the search parameters ( $c_1, c_2, \theta, MAX\_Iteration$ ) and initialize the swarm randomly
2: for each particle  $i$  in the swarm Do
3:   for each dimension  $j$  on the solution vector Do
4:     // initial population ( $k = 0$ ) can be generated with the uniformly distributed solutions in the search region
5:      $x_{ij}(0) = x_{min} + rand * (x_{max} - x_{min})$ 
        $v_{ij}(0) = v_{min} + rand * (v_{max} - v_{min})$  // particles' position and velocity
6:   end for
7: // Calculate the fitness function value for each particle by using the proposed CFA based decoding procedure
8:   The fitness function value;  $f[x_{ij}(k)]$  is evaluated for each particle from the decoding of the chromosome for the transportation tree
9: // Initialize particle's personal best solution,  $x_{ij}^{pbest}$  (set local best position)
10:  if  $k = 0$ , then  $x_{ij}^{pbest}(0) = x_{ij}(0)$ 
11:  else if  $f[x_{ij}(k)] < f[x_{ij}^{pbest}(k)]$ 
        $x_{ij}^{pbest}(k) = x_{ij}(k)$ 
12:  end if
13: // Set global best position as the best particle personal best value
14:  if  $f[x_{ij}^{pbest}(k)] \leq f[x_{ij}^{gbest}(k)]$ , then  $x_{ij}^{gbest}(k) = x_{ij}^{pbest}(k)$ 
15:  end if
16: end for
17: // Calculate the velocity vector for each particle and update the positions of particles
18: for each particle  $i$  in the swarm Do
19:   for each dimension  $j$  on the solution vector Do
20:      $v_{ij}(k) = c_1 * r_1 * \{x_{ij}^{pbest}(k) - x_{ij}(k)\} + c_2 * r_2 * \{x_{ij}^{gbest}(k) - x_{ij}(k)\} + lw_k * v_{ij}(k-1)$ 
        $x_{ij}(k) = x_{ij}(k-1) + v_{ij}(k)$ 
        $lw_k = \theta * lw_{k-1}$ 
21:   end for
22: end for
23: // advance iteration
24:  $k = k + 1$ 
25: Repeat Until //  $k$  exceeds a maximum number of iterations
26:  $k > MAX\_Iteration$ 

```

In initialization phase of this algorithm, each particle is represented by a random initial population and an initial velocity. By utilizing the current information in the swarm, each particle searches for better positions in solution space and updates its velocity. Actually, there are three main attributes related to each particle (Nearchou, 2011): its current position, its personal best position achieved so far and its current velocity. Finally, flowchart of the proposed direct solution approach for solving both balanced and unbalanced FFTP's is presented in Figure 2.19. Indeed, as it is obviously seen from this figure that the proposed approach combines priority-based encoding, CFA based fuzzy decoding procedure with a fuzzy ranking method and the PSO algorithm in an aggregated manner. In summary, priority-based encoding is utilized for solution representation of transportation networks.

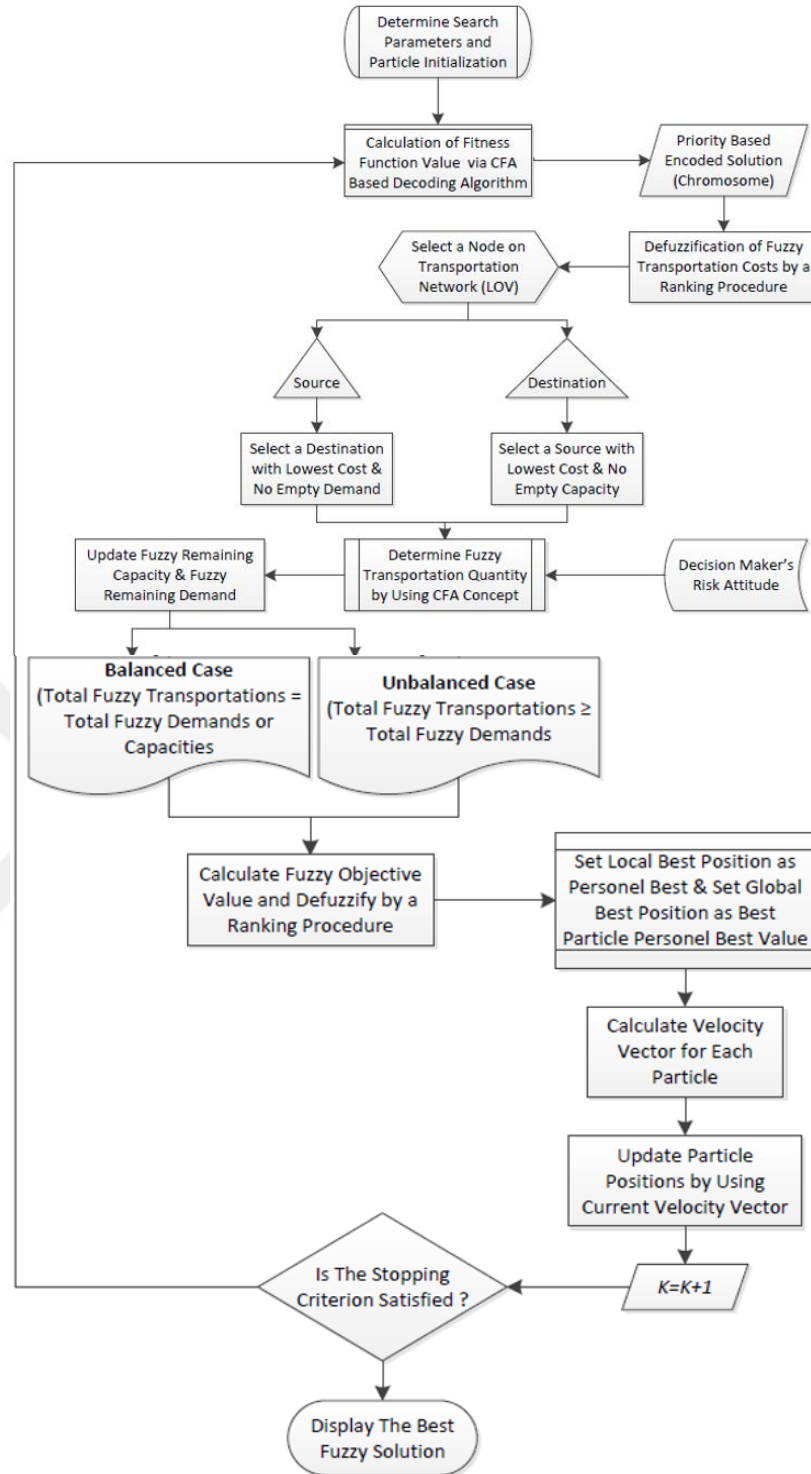


Figure 2.19 Schematic depiction of the proposed direct solution approach for FFTPs

The fitness function value and the entire fuzzy solution are obtained from the CFA based decoding procedure. Selection of the closest node to a specified node with maximal priority is performed after defuzzifying the fuzzy transportation costs and lastly the best fuzzy efficient solution is achieved by applying PSO algorithm.

2.7 Computational Experiments and Comparisons with the Existing Methods

In order to show the validity and applicability of the proposed direct and indirect solution approaches and compare them with the existing methods from the literature, some numerical examples are generated for the aforementioned types of FFTPs in Section 2.4.

2.7.1 Numerical Examples and Comparisons with Methods Incorporating Fuzzy Decision Variables

In each example, three sources (S1, S2, S3) and four destinations (D1, D2, D3, D4) are considered and the related fuzzy data such as unit transportation cost, availability of the commodity at each source and the demands of the destinations for these FFTPs are given in Table 2.7.

Table 2.7 Fuzzy data for five different types of FFTPs

Problem Type		S1	S2	S3	Demand (units)
Type-1	D1	(\$8, \$10, \$10.8)	(\$14, \$15, \$16)	(\$18.4, \$20, \$21)	(6.2, 7, 7.8)
	D2	(\$20.4, \$22, \$24)	(\$18.2, \$20, \$22)	(\$9.6, \$12, \$13)	(8.9, 10, 11.1)
	D3	(\$8, \$10, \$10.6)	(\$10, \$12, \$13)	(\$7.8, \$10, \$10.8)	(6.5, 8, 9.5)
	D4	(\$18.8, \$20, \$22)	(\$6, \$8, \$8.8)	(\$14, \$15, \$16)	(7.8, 9, 10.2)
	Supply (units)	(7.2, 8, 8.8)	(12, 14, 16)	(10.2, 12, 13.8)	
Type-2	D1	(\$17, \$19, \$21)	(\$17, \$19, \$21)	(\$22, \$25, \$27)	(250, 300, 350)
	D2	(\$15, \$16, \$17)	(\$12, \$14, \$16)	(\$18, \$20, \$22)	(300, 350, 400)
	D3	(\$15, \$16, \$17)	(\$14, \$16, \$18)	(\$20, \$21, \$23)	(250, 300, 350)
	D4	(\$16, \$18, \$20)	(\$11, \$13, \$15)	(\$20, \$22, \$24)	(300, 350, 400)
	Supply	(350, 400, 450)	(300, 350, 400)	(100, 150, 200)	
Type-3	D1	(\$17, \$19, \$21)	(\$17, \$19, \$21)	(\$22, \$25, \$27)	(250, 300, 350)
	D2	(\$15, \$16, \$17)	(\$12, \$14, \$16)	(\$18, \$20, \$22)	(300, 350, 400)
	D3	(\$15, \$16, \$17)	(\$14, \$16, \$18)	(\$20, \$21, \$23)	(250, 300, 350)
	D4	(\$16, \$18, \$20)	(\$11, \$13, \$15)	(\$20, \$22, \$24)	(300, 350, 400)
	Supply	(550, 650, 800)	(550, 700, 850)	(600, 800, 1000)	
Type-4	D1	(\$17, \$19, \$21)	(\$17, \$19, \$21)	(\$22, \$25, \$27)	(250, 300, 350)
	D2	(\$15, \$16, \$17)	(\$12, \$14, \$16)	(\$18, \$20, \$22)	(300, 350, 400)
	D3	(\$15, \$16, \$17)	(\$14, \$16, \$18)	(\$20, \$21, \$23)	(250, 300, 350)
	D4	(\$16, \$18, \$20)	(\$11, \$13, \$15)	(\$20, \$22, \$24)	(300, 350, 400)
	Supply	(400, 450, 600)	(450, 500, 600)	(450, 550, 800)	
Type-5	D1	(\$17, \$19, \$21)	(\$17, \$19, \$21)	(\$22, \$25, \$27)	(250, 300, 350)
	D2	(\$15, \$16, \$17)	(\$12, \$14, \$16)	(\$18, \$20, \$22)	(300, 350, 400)
	D3	(\$15, \$16, \$17)	(\$14, \$16, \$18)	(\$20, \$21, \$23)	(250, 300, 350)
	D4	(\$16, \$18, \$20)	(\$11, \$13, \$15)	(\$20, \$22, \$24)	(300, 350, 400)
	Supply	(300, 350, 450)	(300, 350, 400)	(300, 350, 400)	

In detail, type-1 FFTP or balanced case is selected from the literature (Ezzati et al., 2015). For this balanced transportation case given in Table 2.7, when the α -cut level is set to zero, the crisp equivalent LP model which is provided by our proposed indirect solution approach will give infeasible solution for a risk-averse person (where Δ is

equal to zero). Actually, this situation corresponds to the risk-free solution or the crisp inequality constraints between the base variables. On the other hand, fuzzy efficient solutions of this FFTP type $\left(\Delta = \sqrt{2}/2 \text{ and } \Delta = \sqrt{2}\right)$ can be obtained by the proposed approaches for risk neutral and risk seekers. In fact, these solutions can be provided in case of fuzzy equality constraints between the base variables of fuzzy components. The expanded mathematical form of type-1 FFTP is given as follows:

$$\begin{aligned} \text{Min } Z \cong & (8, 10, 10.8) \otimes x_{11} \oplus (20.4, 22, 24) \otimes x_{12} \oplus (8, 10, 10.6) \otimes x_{13} \oplus (18.8, 20, 22) \otimes x_{14} \\ & \oplus (14, 15, 16) \otimes \tilde{x}_{21} \oplus (18.2, 20, 22) \otimes \tilde{x}_{22} \oplus (10, 12, 13) \otimes \tilde{x}_{23} \oplus (6, 8, 8.8) \otimes \tilde{x}_{24} \end{aligned} \quad (2.99)$$

$$\oplus (18.4, 20, 21) \otimes x_{31} \oplus (9.6, 12, 13) \otimes x_{32} \oplus (7.8, 10, 10.8) \otimes x_{33} \oplus (14, 15, 16) \otimes x_{34} \quad (2.100)$$

$$\tilde{x}_{11} \oplus \tilde{x}_{12} \oplus \tilde{x}_{13} \oplus \tilde{x}_{14} \cong (7.2, 8, 8.8) \quad (2.101)$$

$$\tilde{x}_{21} \oplus \tilde{x}_{22} \oplus \tilde{x}_{23} \oplus \tilde{x}_{24} \cong (12, 14, 16) \quad (2.102)$$

$$\tilde{x}_{31} \oplus \tilde{x}_{32} \oplus \tilde{x}_{33} \oplus \tilde{x}_{34} \cong (10.2, 12, 13.8) \quad (2.103)$$

$$\tilde{x}_{11} \oplus \tilde{x}_{21} \oplus \tilde{x}_{31} \cong (6.2, 7, 7.8) \quad (2.104)$$

$$\tilde{x}_{12} \oplus \tilde{x}_{22} \oplus \tilde{x}_{32} \cong (8.9, 10, 11.1) \quad (2.105)$$

$$\tilde{x}_{13} \oplus \tilde{x}_{23} \oplus \tilde{x}_{33} \cong (6.5, 8, 9.5) \quad (2.106)$$

$$\tilde{x}_{14} \oplus \tilde{x}_{24} \oplus \tilde{x}_{34} \cong (7.8, 9, 10.2) \quad (2.107)$$

$$\tilde{x}_{11}, \tilde{x}_{12}, \tilde{x}_{13}, \dots, \tilde{x}_{33}, \tilde{x}_{34} \succeq (0, 0, 0) \text{ non-negative fuzzy numbers} \quad (2.107)$$

In order to generate the fuzzy efficient solutions of type-1 balanced FFTP, LINGO 15.0 software is utilized to solve crisp equivalent LP model in case of proposed indirect solution approach. The results are presented in Table 2.8 for risk-neutral and risk seekers. Additionally, the membership functions related to the total outgoing flows against to fuzzy total capacities are presented in Figure 2.20. Similarly, the difference between the membership functions according to different Δ values are depicted for the incoming flows to the destinations in Figure 2.21.

Table 2.8 Results of type-1 FFTP by proposed indirect solution approach

Sources/ Destinations	D1			D2		D3		D4	
	$\Delta = \sqrt{2}/2$	$\Delta = \sqrt{2}$	$\Delta = \sqrt{2}/2$	$\Delta = \sqrt{2}$	$\Delta = \sqrt{2}/2$	$\Delta = \sqrt{2}$	$\Delta = \sqrt{2}/2$	$\Delta = \sqrt{2}$	$\Delta = \sqrt{2}$
S1	(7,7,7)	(6.2,7,7.8)	(0,0,0)	(0,0,0)	(1,1,1)	(1,1,1)	(0,0,0)	(0,0,0)	(0,0,0)
S2	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(5,5,5)	(4.2,5,5.8)	(9,9,9)	(7.8,9,10.2)	(7.8,9,10.2)
S3	(0,0,0)	(0,0,0)	(10,10,10)	(8.9,10,11.1)	(2,2,2)	(1.3,2,2.7)	(0,0,0)	(0,0,0)	(0,0,0)

Hence, the optimal objective function value of type-1 FFTP is achieved for a risk-neutral person as $\tilde{Z}^*_{\text{Proposed method}} = (\$279.6, 352, \$382)$. Moreover, by substituting the decision variables (in Table 2.8) in the objective function, optimal value of the

type-1 FFTP can be obtained for a risk-seeker as $\tilde{Z}^*_{Proposed\ method} = (\$241.98, \$352, \$433.46)$. Furthermore, it is clearly understood from the above results that the proposed CFA based method give the same objective function value but with different decision variables' values with Kumar et al.'s method (2011) for a risk seeker ($\Delta = \sqrt{2}$).

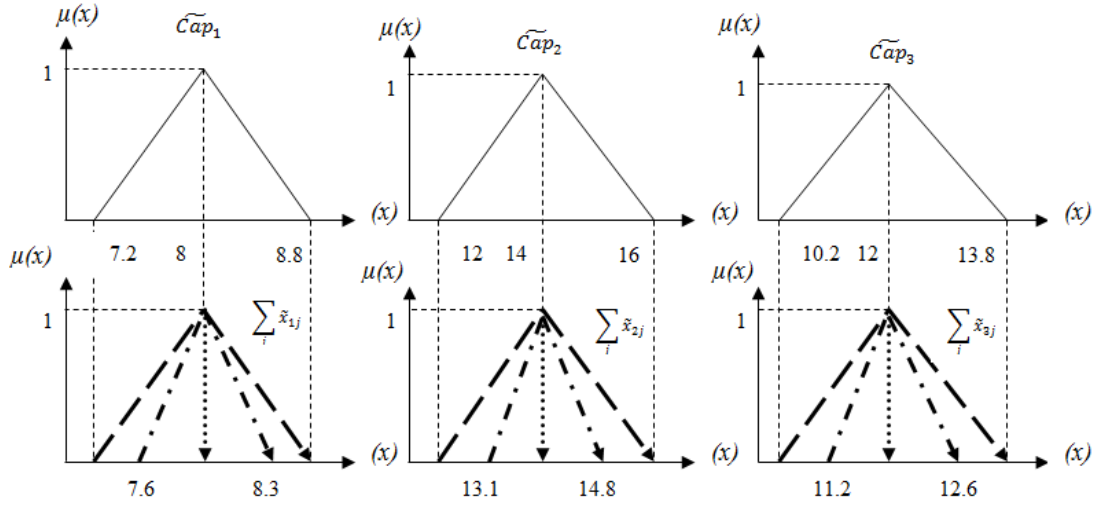


Figure 2.20 Membership functions for total outgoing flows from the sources (Type-1 FFTP)

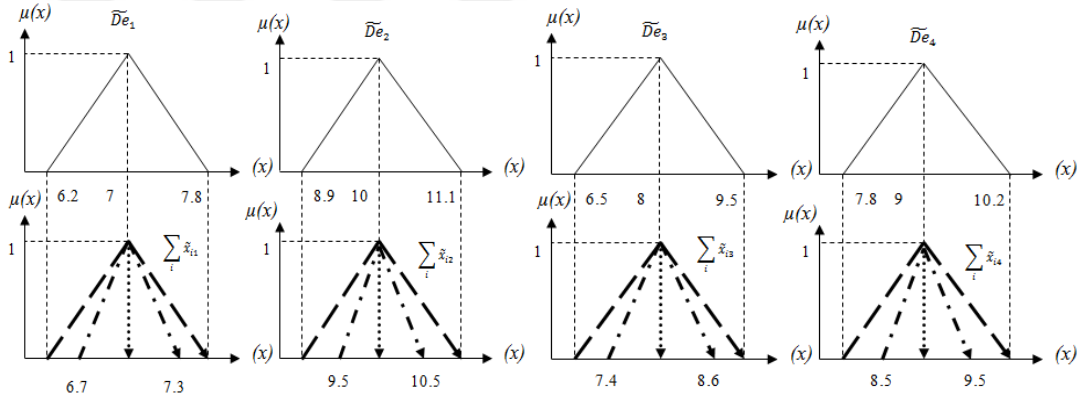


Figure 2.21 Membership functions for total incoming flows to the destinations (Type-1 FFTP)

According to the computational results, more precise and partially risk-free solutions will be provided when the risk sensitivity of the decision maker increases or the value of Δ decreases. Finally, the membership function of the fuzzy objective value can also be obtained as shown in Figure 2.22 by considering different Δ values. When the proposed direct solution approach is applied, the following results are yielded which are reported in Table 2.9. In the fuzzy optimization phase of the proposed direct solution approach for the given balanced FFTP, cognitive and social parameters for

PSO algorithm are taken as 2 and 1.5, respectively. The initial value of inertia weight is 0.9 and particle population size is set to 2.

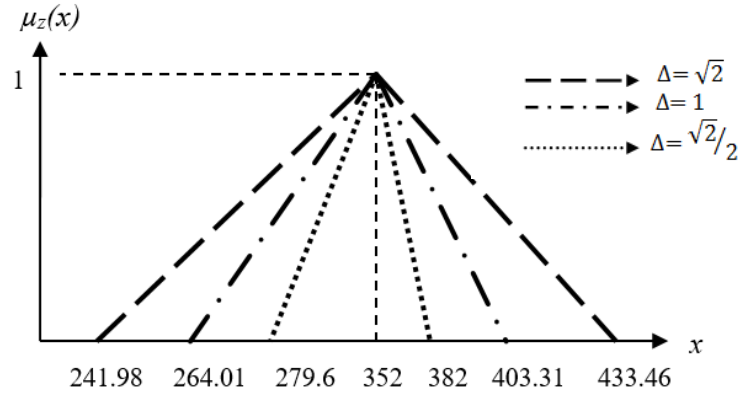


Figure 2.22 Membership functions of fuzzy objective value for Type-1 FFTP

Since the examined problem is a trivial FFTP, convergence to the fuzzy efficient solutions is provided within 10 generations. The convergence graphs of the best fuzzy solutions found by the proposed direct solution approach with respect to different risk attitudes (Δ values) are presented in Figure 2.23. Actually, this figure points out that improvements can be achieved rapidly in terms of total fuzzy transportation cost by employing the proposed fuzzy decoding procedure embedded into a PSO algorithm.

Table 2.9 Fuzzy efficient solutions of balanced FFTP case with different risk attitudes and α -cut levels

S/D	$\Delta = \sqrt{2}$ (Risk-seeker)			$\Delta = 1.0$ (Partially risk-seeker)			$\Delta = \sqrt{2}/2$ (Risk-neutral)		
	$\alpha = 0$	$\alpha = 0.5$	$\alpha = 1.0$	$\alpha = 0$	$\alpha = 0.5$	$\alpha = 1.0$	$\alpha = 0$	$\alpha = 0.5$	$\alpha = 1.0$
S1-D1	[6.2, 7.8]	[6.6, 7.4]	[7, 7]	[6.67, 7.33]	[6.83, 7.16]	[7, 7]	[7, 7]	[7, 7]	[7, 7]
S1-D3	[1, 1]	[1, 1]	[1, 1]	[1, 1]	[1, 1]	[1, 1]	[1, 1]	[1, 1]	[1, 1]
S2-D3	[4.2, 5.8]	[4.6, 5.4]	[5, 5]	[4.67, 5.33]	[4.83, 5.16]	[5, 5]	[5, 5]	[5, 5]	[5, 5]
S2-D4	[7.8, 10.2]	[8.4, 9.6]	[9, 9]	[8.5, 9.49]	[8.75, 9.25]	[9, 9]	[9, 9]	[9, 9]	[9, 9]
S3-D2	[8.9, 11.1]	[9.45, 10.55]	[10, 10]	[9.54, 10.45]	[9.77, 10.23]	[10, 10]	[10, 10]	[10, 10]	[10, 10]
S3-D3	[1.3, 2.7]	[1.65, 2.35]	[2, 2]	[1.71, 2.29]	[1.85, 2.15]	[2, 2]	[2, 2]	[2, 2]	[2, 2]
Fuzzy Objective	[241.9, 433.5]	[294.5, 391.7]	[352, 352]	[264.1, 403.3]	[306.9, 377.2]	[352, 352]	[279.6, 382]	[315.8, 367]	[352, 352]

In addition, it is obviously seen from the fuzzy convergence graph that faster convergence to fuzzy efficient solution can be maintained when risk sensitivity of the decision maker increases or the value of Δ decreases.

It is not possible to find any feasible solution for type-2 FFTP that is shown in Table 2.7. Because, fuzzy total capacities (750, 900, 1050) are not sufficient so as to satisfy fuzzy total demands (100, 1300, 1500). For this reason, there is no feasible and applicable solution for this type of FFTPs for any α -cut level.

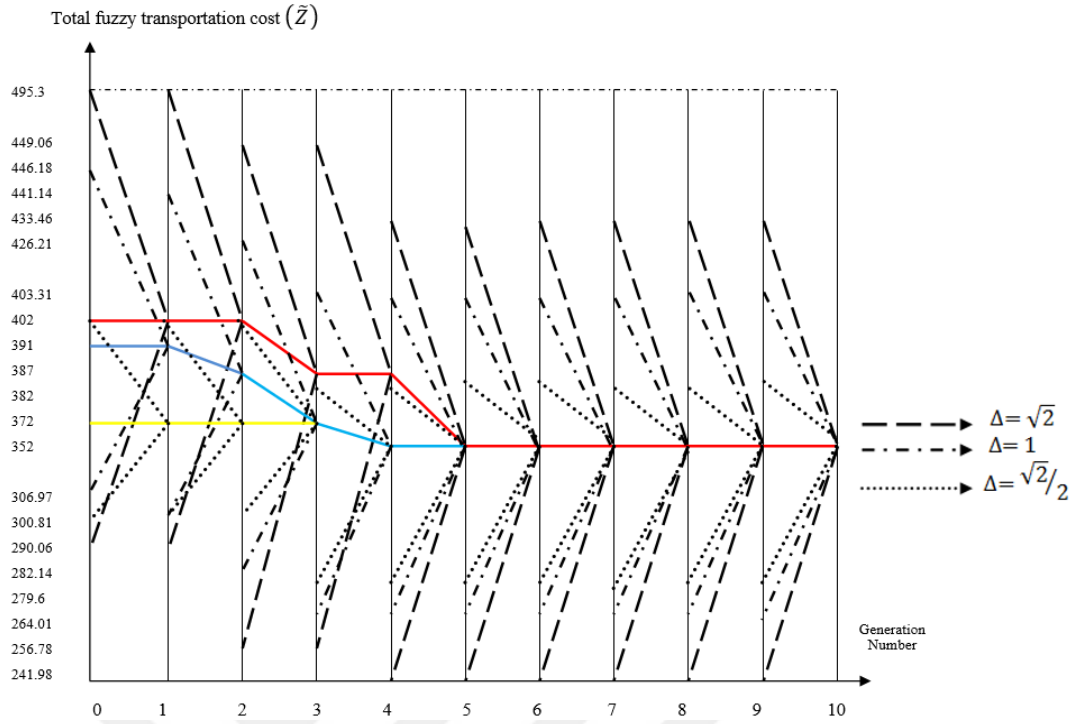


Figure 2.23 Convergence graphs of fuzzy objective value with different risk attitudes (type-1 FFTP)

In addition to the balanced FFTP, numerical examples on different types of unbalanced FFTPs with the same problem size are also presented for direct and indirect solution via the proposed CFA approaches. The regarding fuzzy data is given by the following Figure 2.24 for type-3 FFTP.

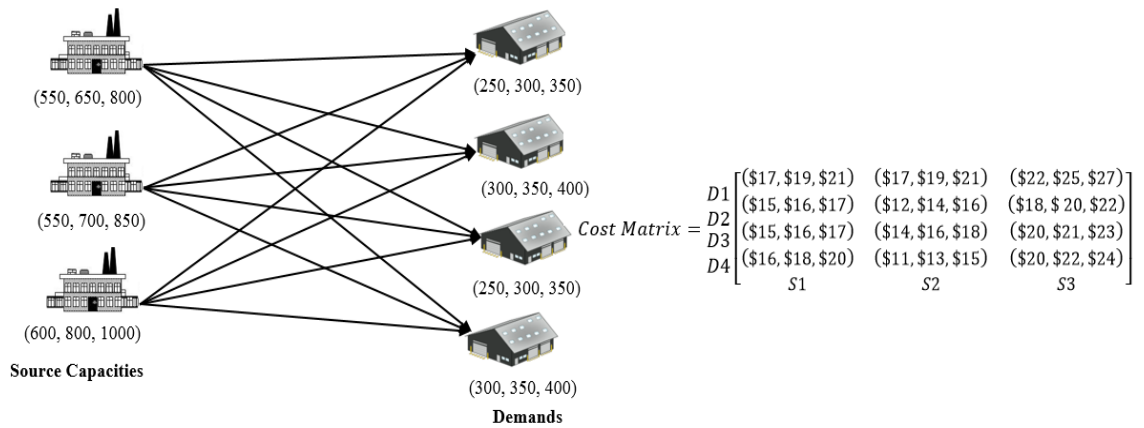


Figure 2.24 Fuzzy data for the unbalanced type-3 FFTP

The expanded mathematical formulation of this unbalanced type-3 FFTP can be given as followings:

$$\begin{aligned} \text{Min } Z \cong & ((17, 19, 21) \otimes x_{11} \oplus (15, 16, 17) \otimes x_{12} \oplus (15, 16, 17) \otimes x_{13} \oplus (16, 18, 20) \otimes x_{14} \\ & \oplus (17, 19, 21) \otimes x_{21} \oplus (12, 14, 16) \otimes x_{22} \oplus (14, 16, 18) \otimes x_{23} \oplus (11, 13, 15) \otimes x_{24} \oplus \\ & (22, 25, 27) \otimes x_{31} \oplus (18, 20, 22) \otimes x_{32} \oplus (20, 21, 23) \otimes x_{33} \oplus (20, 22, 24) \otimes x_{34} \end{aligned} \quad (2.108)$$

$$\tilde{x}_{11} \oplus \tilde{x}_{12} \oplus \tilde{x}_{13} \oplus \tilde{x}_{14} \lesssim (550, 650, 800) \quad (2.109)$$

$$\tilde{x}_{21} \oplus \tilde{x}_{22} \oplus \tilde{x}_{23} \oplus \tilde{x}_{24} \lesssim (550, 700, 850) \quad (2.110)$$

$$\tilde{x}_{31} \oplus \tilde{x}_{32} \oplus \tilde{x}_{33} \oplus \tilde{x}_{34} \lesssim (600, 800, 1000) \quad (2.111)$$

$$\tilde{x}_{11} \oplus \tilde{x}_{21} \oplus \tilde{x}_{31} \gtrsim (250, 300, 350) \quad (2.112)$$

$$\tilde{x}_{12} \oplus \tilde{x}_{22} \oplus \tilde{x}_{32} \gtrsim (300, 350, 400) \quad (2.113)$$

$$\tilde{x}_{13} \oplus \tilde{x}_{23} \oplus \tilde{x}_{33} \gtrsim (250, 300, 350) \quad (2.114)$$

$$\tilde{x}_{14} \oplus \tilde{x}_{24} \oplus \tilde{x}_{34} \gtrsim (300, 350, 400) \quad (2.115)$$

$$\tilde{x}_{11}, \tilde{x}_{12}, \tilde{x}_{13}, \dots, \tilde{x}_{33}, \tilde{x}_{34} \gtrsim (0, 0, 0) \text{ non-negative fuzzy numbers} \quad (2.116)$$

For type-3 FFTP, when the numerical example is transformed into the crisp equivalent via the existing methods of Kumar et al. (2010) and (2011) and Ezzati et al. (2015), the following results given in Table 2.10 are yielded by solving the provided crisp LP models. Hence, the best fuzzy objective values for this kind of transportation case are obtained through these methods as $\tilde{Z}^*_{\text{Kumar's method}} = (\$15050, \$20050, \$25750)$ and $\tilde{Z}^*_{\text{Ezzati's method}} = (\$15050, \$20050, \$27150)$.

Table 2.10 Fuzzy solutions of type-3 FFTP by utilizing the existing methods

Destinations /Sources	S1		S2		S3	
	Kumar et al.'s method	Ezzati et al.'s method	Kumar et al.'s method	Ezzati et al.'s method	Kumar et al.'s method	Ezzati et al.'s method
D1	(250,250,300)	(250,300,300)	(0,50,50)	(0,0,0)	(0,0,0)	(0,50,50)
D2	(50,50,50)	(50,50,50)	(250,300,350)	(250,300,300)	(0,0,0)	(0,50,50)
D3	(250,300,350)	(250,250,250)	(0,0,0)	(0,50,50)	(0,0,0)	(0,50,50)
D4	(0,0,0)	(0,0,0)	(300,350,400)	(300,350,350)	(0,0,0)	(0,50,50)

However, both of these methods may not generate applicable solutions for a risk-averse decision maker. In detail, when these fuzzy solutions provided by Kumar et al.'s method (2010) and (2011) are realized, the following negative fuzzy remaining capacities will occur:

$$\text{For source 1: } (550, 650, 800) \ominus (250, 250, 300) \ominus (50, 50, 50) \ominus (250, 300, 350) = (-150, 50, 250) \quad (2.117)$$

$$\text{For source 2: } (550, 700, 850) \ominus (0, 50, 50) \ominus (250, 300, 350) \ominus (300, 350, 400) = (-250, 0, 300) \quad (2.118)$$

$$\text{For source 3: } (600, 800, 1000) \ominus (0, 0, 0) \ominus (0, 0, 0) \ominus (0, 0, 0) \ominus (0, 0, 0) = (600, 800, 1000) \quad (2.119)$$

Based on these calculations, it is clear that demands may not be satisfied at the end of the transportation process since some of the fuzzy remaining capacities are not non-negative fuzzy numbers. In other words, while realizing the transportation process, capacities of the sources may become insufficient.

A simple illustration for the risk of non-meeting the demands is depicted in Figure 2.25. In order to show the capacity inadequacy of source-1 in the above example, the membership functions for transportation operation-3 (the membership function of remaining capacity of source-1 and remaining demand of destination-3) are also given in Figure 2.26. It can be seen from Figures 2.25 and 2.26 that the capacity of source-1 may become insufficient and the demand of destination-3 cannot be fully satisfied after the transportation processes. Moreover, it is obvious that after realizing the transportation operations (operation-1 and operation-5), there may be still positive remaining demand at destination-1. So, the risk of unsatisfactory demand for destination-1 may also occur.

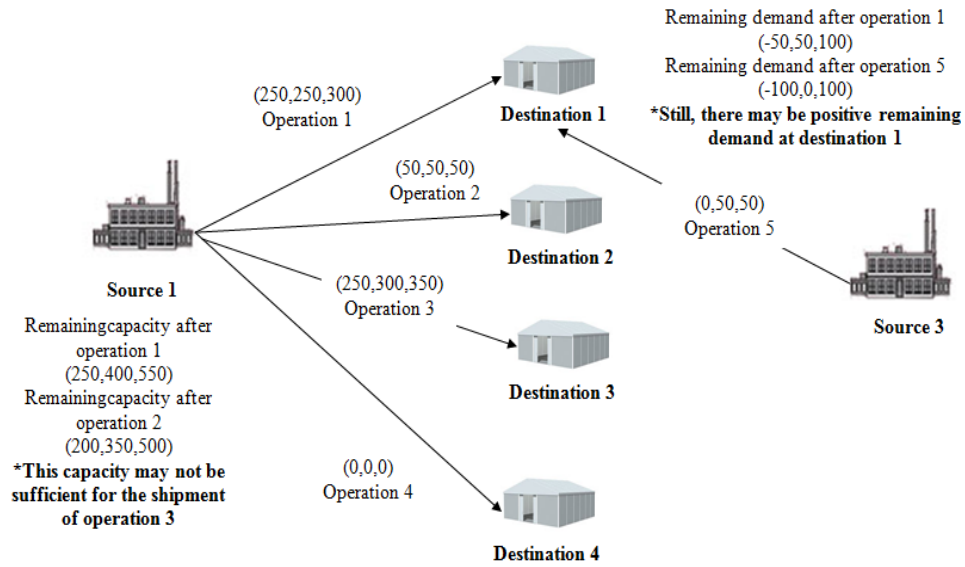


Figure 2.25 A schematic depiction for risk of demand unsatisfactory and capacity unavailability

In fact, the obtained solutions via these methods may present useful information for the decision maker who is risk seeker or insensitive to risk. However, these solutions cannot be accepted by a risk-averse person who is sensitive to risk. Thus, while realizing the solution, the fuzzy remaining capacities should not include any negative element. For a more clear explanation, remaining capacities should be non-negative

fuzzy numbers as the basic requirement of the fuzzy linear programming. The method of Ezzati et al. (2015) also suffers from the same problem.

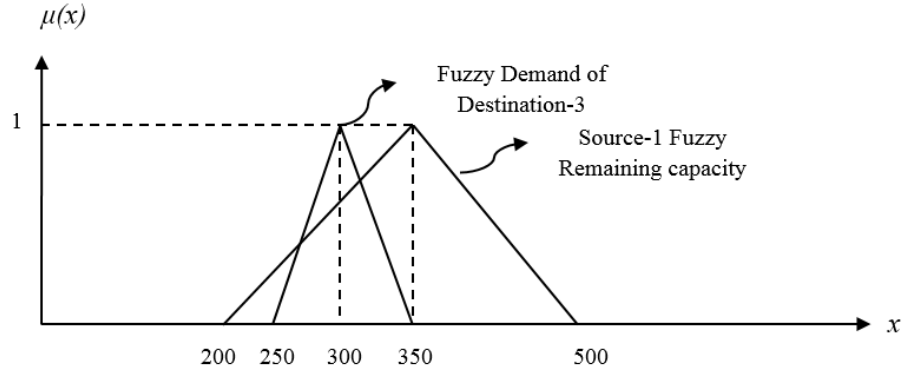


Figure 2.26 Membership functions for remaining capacity of source-1 and demand of destination-3

Similarly, fuzzy remaining demands of the destinations may have positive elements after realizing the fuzzy solutions obtained by Kumar et al.'s method (2010) and (2011) as follows:

$$\text{For destination 1: } (250,300,350) \ominus (250,250,300) \ominus (0,50,50) = (-50,0, \mathbf{100}) \quad (2.120)$$

$$\text{For destination 2: } (300,350,400) \ominus (50,50,50) \ominus (250,300,350) = (-100,0, \mathbf{100}) \quad (2.121)$$

$$\text{For destination 3: } (250,300,350) \ominus (250,300,350) = (-100,0, \mathbf{100}) \quad (2.122)$$

$$\text{For destination 4: } (300,350,400) \ominus (300,350,400) = (-100,0, \mathbf{100}) \quad (2.123)$$

Due to the fact that standard fuzzy subtraction operation is not an inverse operation, all of the fuzzy remaining demands involve positive elements at the right margin of fuzzy numbers. Thus, some of the destinations' demands may not be fully satisfied. In other words, there is risk of not meeting demands. Briefly, provided solutions by utilizing these methods seem to be feasible in terms of the addition operator in classical standard fuzzy arithmetic. But, it is clear that when realizing these solutions, inapplicability problem may arise. In order to obtain applicable and more reliable solutions under different risk attitudes of the decision makers, the proposed CFA based approaches can be an appropriate method. By utilizing the proposed CFA based direct and indirect solution approaches, more confidential solutions can be acquired for the decision maker(s) who are risk-averse or partially risk-averse. Furthermore, it should also be noted that when the decision maker is risk-averse, the obtained solutions are crisp. In fact, this is a desirable situation for most of the risk-averse decision makers.

However, for the decision makers who are risk seekers, fuzzy efficient solutions can be acceptable ones as it is given by Table 2.11. When type-3 FFTP is solved by using CFA based indirect solution approach, different optimal solutions can be provided according to Δ values between $[0, \sqrt{2}]$. The proposed method can offer various solutions for this type of FFTPs under the consideration of different risk attitudes of the decision makers. In order to visualize the risk sensitivity degree of the decision makers, a scale is derived as depicted in Figure 2.27.

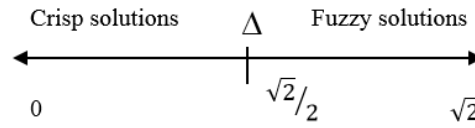


Figure 2.27 Scale for representing risk sensitivity of decision maker(s)

Table 2.11 Fuzzy efficient solutions by CFA based indirect solution approach with different risk attitudes (type-3 FFTP)

Sources/ Destinations	$\Delta = 0$ (Risk-averse)	$\Delta = 0.35$ (Partially risk-averse)	$\Delta = \frac{\sqrt{2}}{2}$ (Risk-neutral)	$\Delta = 1.05$ (Partially risk-seeker)	$\Delta = \sqrt{2}$ (Risk-seeker)
S1-D1	(200,200,200)	(286.6,286.6,286.6)	(300,300,300)	(275.75,300,324.24)	(250,300,350)
S1-D2	(0,0,0)	(0,0,0)	(0,0,0)	(24.24,24.24,24.24)	(50,50,50)
S1-D3	(350,350,350)	(325.2,325.2,325.2)	(300,300,300)	(275.75,300,324.24)	(250,300,350)
S1-D4	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
S2-D1	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
S2-D2	(150,150,150)	(248.9,248.9,248.9)	(350,350,350)	(301.5,325.75,350)	(250,300,350)
S2-D3	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
S2-D4	(400,400,400)	(375.2,375.2,375.2)	(350,350,350)	(325.75,350,374.24)	(300,350,400)
S3-D1	(150,150,150)	(38.63,38.63,38.63)	(0,0,0)	(0,0,0)	(0,0,0)
S3-D2	(250,250,250)	(126.2,126.2,126.2)	(0,0,0)	(0,0,0)	(0,0,0)
S3-D3	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
S3-D4	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
Fuzzy Objective	(22650,25450,28100)	(19989,22504,24981.6)	(17650,19950,22250)	(16389.2,19918.5,23947.3)	(15050,20050,25750)

All of the membership functions for the total outgoing flows from the sources with their fuzzy capacities are displayed in Figure 2.28. Correspondingly, membership functions of the incoming flows to the destinations with their fuzzy demands are drawn as it can be seen from Figure 2.29. The membership function of the fuzzy objective value for type-3 FFTP is presented in Figure 2.30. When risk tolerance of the decision maker is increased (larger values of Δ), the objective function value will decrease as it is seen from Table 2.11 and Figure 2.30. On the other hand, the risk for unavailable capacity of sources and unsatisfactory demand of destinations will increase.

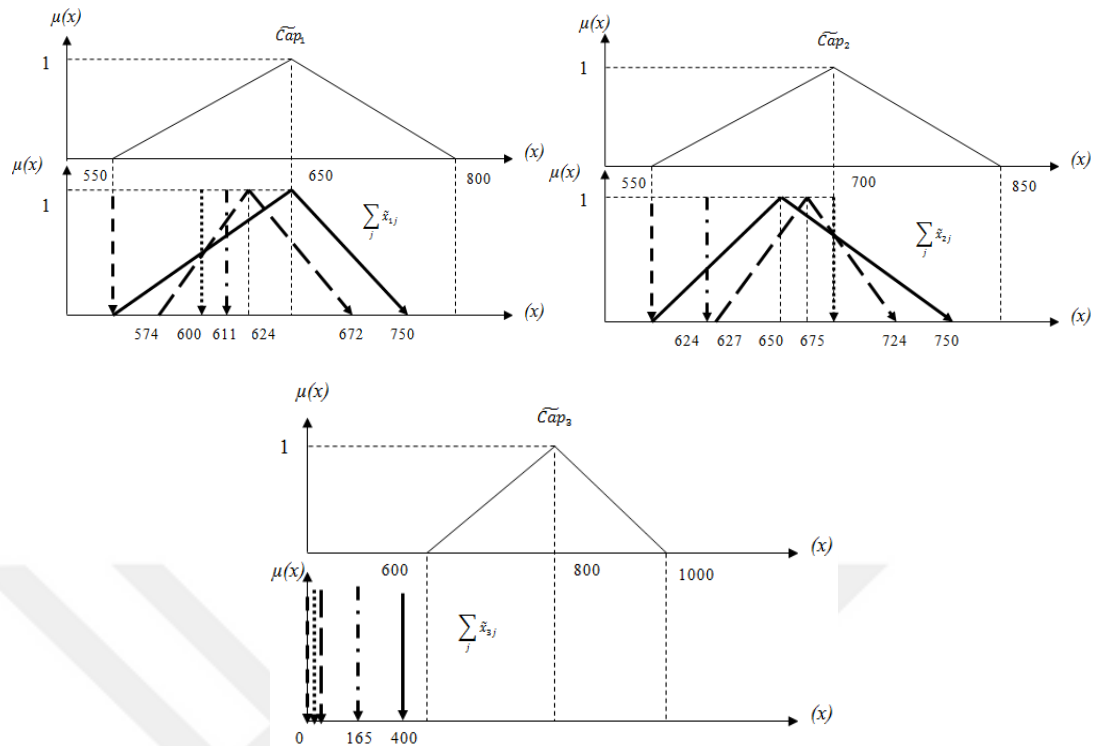


Figure 2.28 Membership functions for outgoing flows according to different Δ values (Type-3 FFTP)

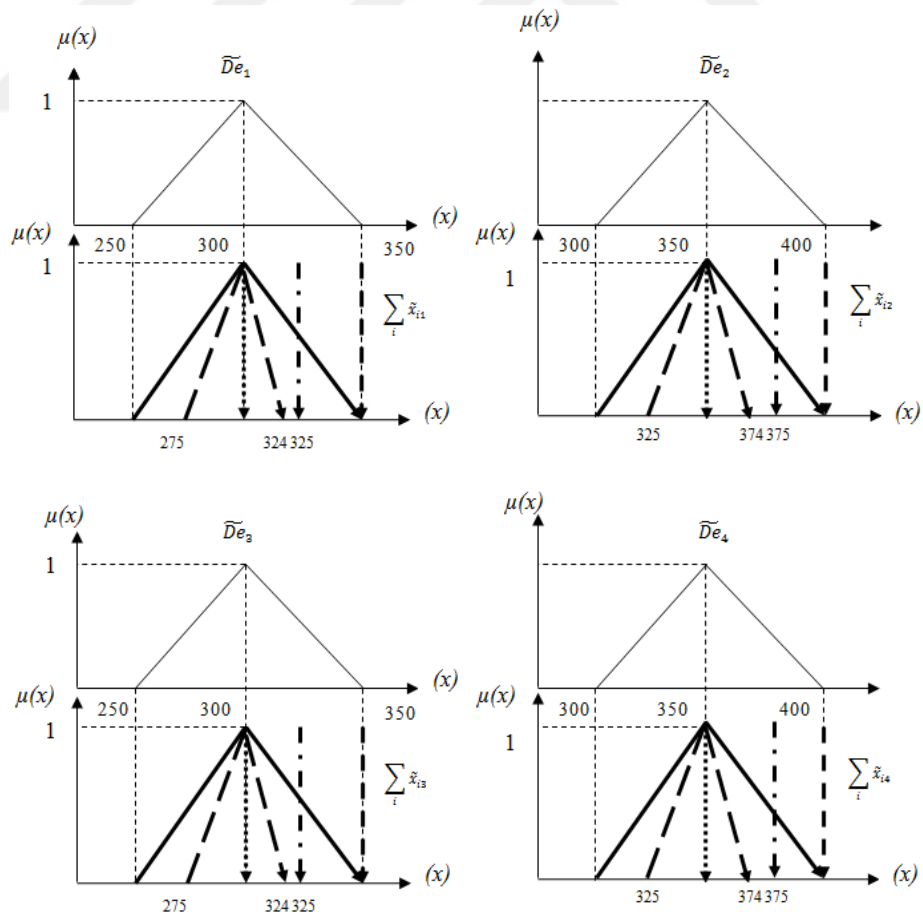


Figure 2.29 Membership functions for incoming flows according to different Δ values (Type-3 FFTP)

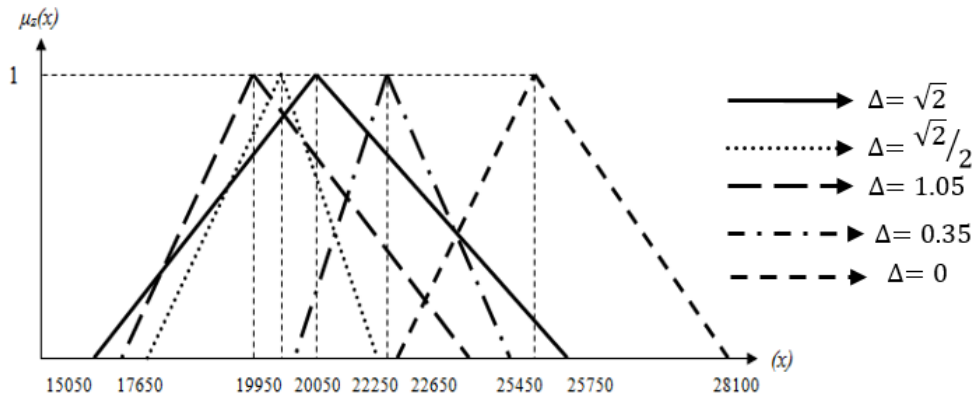


Figure 2.30 Membership functions of fuzzy transportation cost objective for type-3 FFTP

The transportation quantities will take more imprecise values when the risk sensitivity of the decision maker is low (or risk-seeker). This statement is also supported by the Figures 2.28 and 2.29. For instance, when the risk sensitivity of the decision maker is low, there is no shipment from the source-3 which has the highest unit transportation cost. However, there will be more costly extra shipments from source-3 for the risk-averse decision makers.

The fuzzy efficient solutions with respect to different risk attitudes are also presented via the proposed direct solution approach as in Table 2.12 when the α -cut level is set to zero. Figures 2.31 to 2.33 present the convergence graphs of the best fuzzy solutions found by the proposed direct solution approach for the unbalanced type-3 FFTP with respect to different risk attitudes (Δ values). In detail, Figure 2.31 is the convergence of the fuzzy fitness function value of the examined unbalanced type-3 FFTP under risk seeking ($\Delta = \sqrt{2}$).

Table 2.12 Fuzzy efficient solutions of unbalanced type-3 FFTP case ($\alpha = 0$)

S/D	$\Delta = 0$ (Risk-averse)	$\Delta = 0.35$ (Partially risk-averse)	$\Delta = \sqrt{2}/2$ (Risk-neutral)	$\Delta = 1.05$ (Partially risk-seeker)	$\Delta = \sqrt{2}$ (Risk-seeker)
S1-D1	[200, 200]	[286.62, 286.62]	[300, 300]	[275.75, 300]	[250, 350]
S1-D2	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[50, 50]
S1-D3	[350, 350]	[325.25, 325.25]	[300, 300]	[275.75, 324.24]	[250, 350]
S2-D1	[0, 0]	[0, 0]	[0, 0]	[0, 24.24]	[0, 0]
S2-D2	[150, 150]	[248.99, 248.99]	[350, 350]	[325.75, 374.24]	[250, 350]
S2-D4	[400, 400]	[375.25, 375.25]	[350, 350]	[325.75, 374.24]	[300, 400]
S3-D1	[150, 150]	[38.63, 38.63]	[0, 0]	[0, 0]	[0, 0]
S3-D2	[250, 250]	[126.25, 126.25]	[0, 0]	[0, 0]	[0, 0]
Fuzzy Objective	[22650, 28100]	[19989.51, 24981.65]	[17650, 22250]	[16316.45, 23922.98]	[15050, 25750]

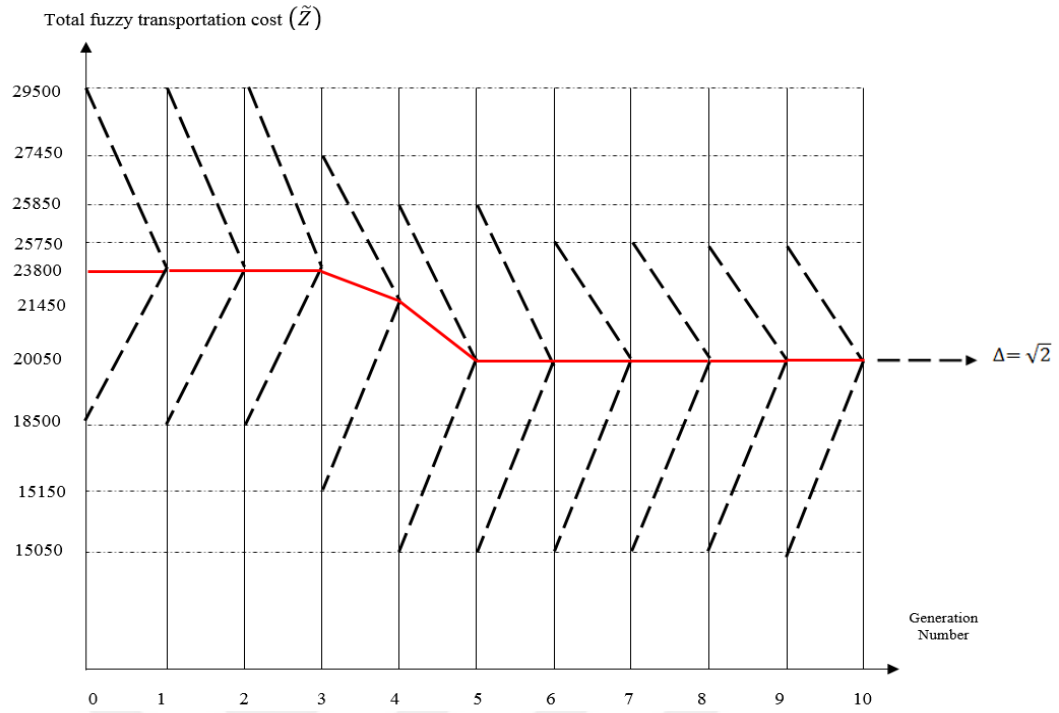


Figure 2.31 Convergence graph of fuzzy objective value under risk seeking for type-3 FFTP

Similarly, fuzzy convergence graphs are also visualized for the risk-averse and risk-neutral decision makers, respectively. Although the generated solutions for the risk-neutral decision maker are crisp ones, the objective function converges to a fuzzy value since the transportation costs are also defined as triangular fuzzy numbers.

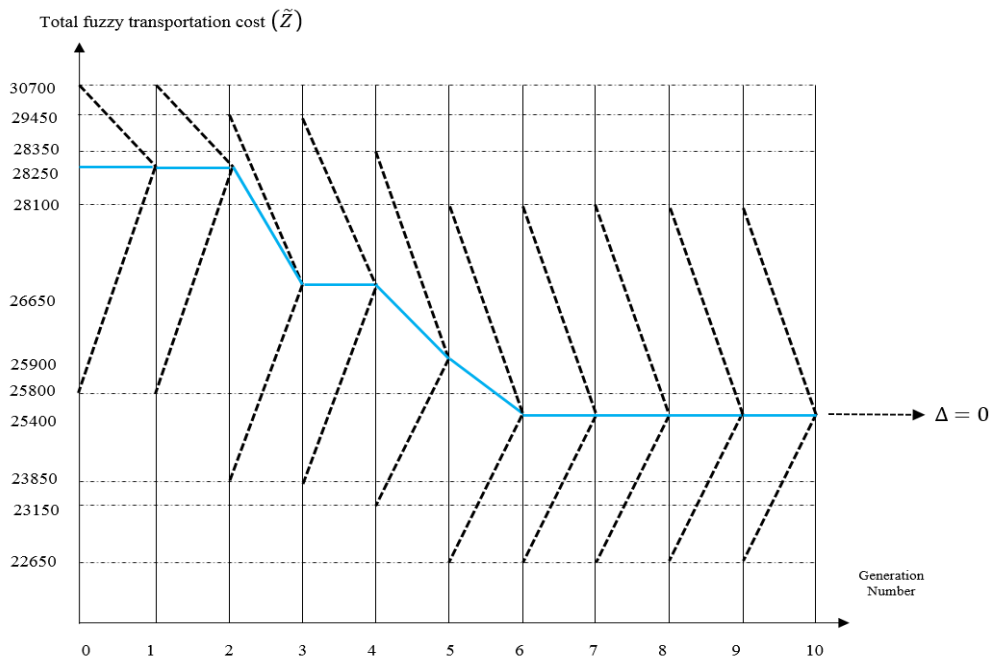


Figure 2.32 Convergence graph of fuzzy objective value under risk aversion for type-3 FFTP

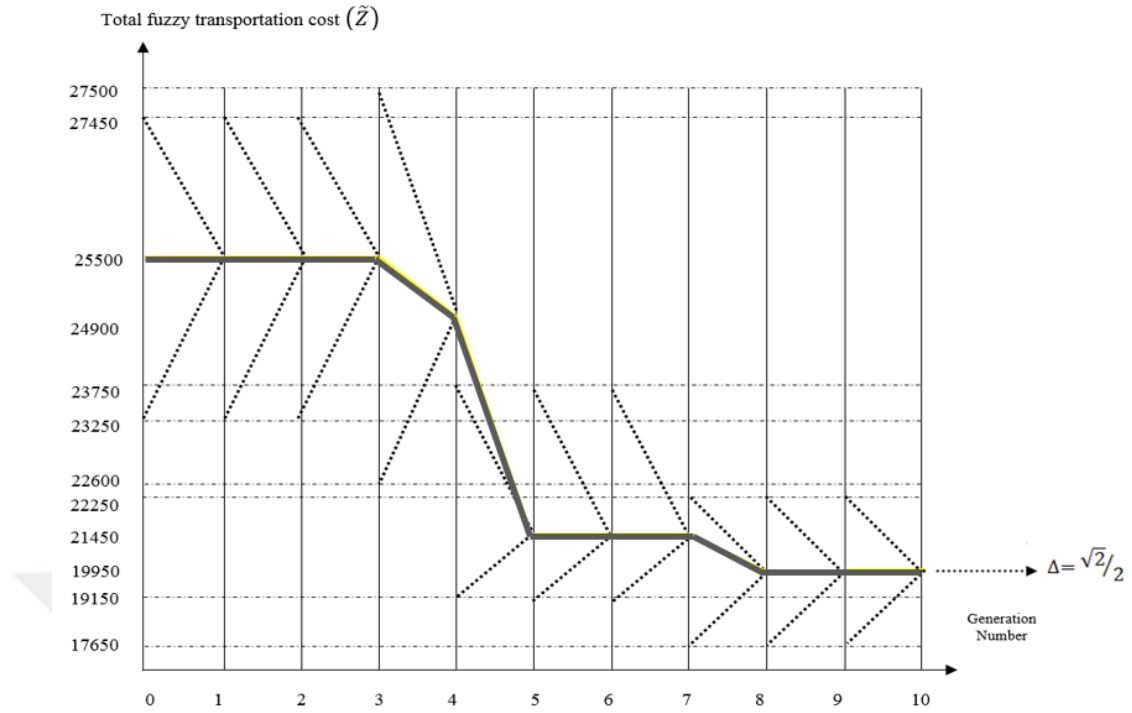


Figure 2.33 Convergence graph of fuzzy objective under risk neutral for type-3 FFTP

In addition, it is clearly seen from Figure 2.31 that the objective function value will converge to a relatively smaller fuzzy number in case of risk-seeking when compared to risk-neutral and risk-aversion. It should also be highlighted that rapid convergence can be maintained under risk-aversion and risk-neutral since the type of the provided solutions is crisp. Besides, less number of iterations may be required for this kind of unbalanced FFTPs in the decoding phase of the proposed direct solution approach.

The membership functions of the fuzzy total capacities and fuzzy total demands are depicted in Figure 2.34 for type-4 FFTP.

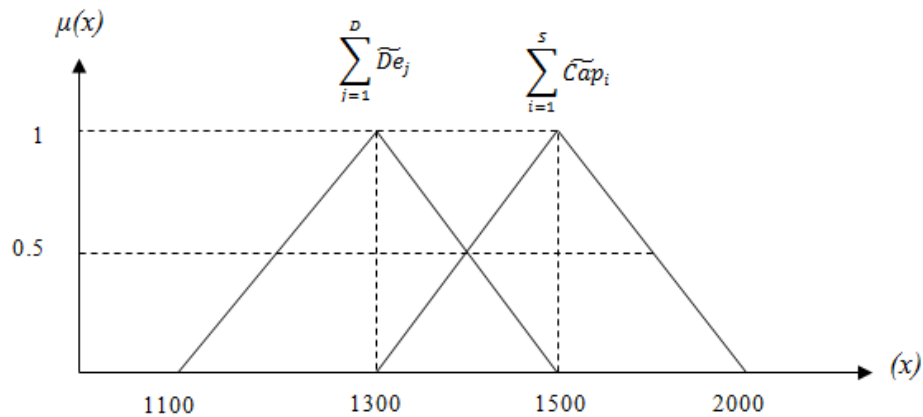


Figure 2.34 Membership functions of fuzzy total capacities and demands for Type-4 FFTP

When the numerical example related to type-4 FFTP is solved, it is clear from Figure 2.34 that there is no feasible risk-free solution ($\Delta=0$) below $\alpha = 0.5$ level. On the other hand, one can provide realizable risk-free solutions for $\alpha \geq 0.5$ level. In fact, decision maker cannot obtain fully risk-free solutions below $\alpha = 0.5$ level. But, if risk sensitivity degree of the decision maker is larger than 0.25, feasible fuzzy solutions can be yielded for $\alpha=0$ level. The obtained fuzzy efficient solutions for type-4 FFTP are given in Table 2.13 by considering different risk attitudes of the decision maker(s).

Table 2.13 Fuzzy efficient solutions by proposed CFA based approaches (type-4 FFTP)

Sources/ Destinations	$\Delta=0$ (Risk-averse)	$\Delta=0.26$ (Partially risk-averse)	$\Delta=\sqrt{2}/2$ (Risk-neutral)	$\Delta=1.05$ (Partially risk-seeker)	$\Delta=\sqrt{2}$ (Risk-seeker)
S1-D1	NA	(331.61, 331.61, 331.61)	(300,300,300)	(275.75,300,311.36)	(250,300,350)
S1-D2	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S1-D3	NA	(105.1, 105.15, 105.15)	(150,150,150)	(150,150,174.24)	(150,150,200)
S1-D4	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S2-D1	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 12.87)	(0, 0, 0)
S2-D2	NA	(95.96, 95.96, 95.96)	(150, 150, 150)	(150,150,174.24)	(150,150,200)
S2-D3	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S2-D4	NA	(381.61, 381.61, 381.61)	(350,350,350)	(325.75,350,374.24)	(300,350,400)
S3-D1	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S3-D2	NA	(285.65, 285.65, 285.65)	(200,200,200)	(175.75,200,200)	(150,200,200)
S3-D3	NA	(226.46, 226.46, 226.46)	(150,150,150)	(125.75,150,150)	(100,150,150)
S3-D4	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
Fuzzy Objective	Infeasible solution	(22235.6, 24756.4, 27504.1)	(19600,21900, 24350)	(17999.7, 21900,26022.9)	(16300, 21900,27800)

Similar to the other types of FFTPs, the membership functions of the total outgoing flows from the sources and total incoming flows to the destinations are revealed as in the Figures 2.35 and 2.36 for the larger values of $\Delta > 0.25$ since there is no feasible solution below this risk sensitivity degree.

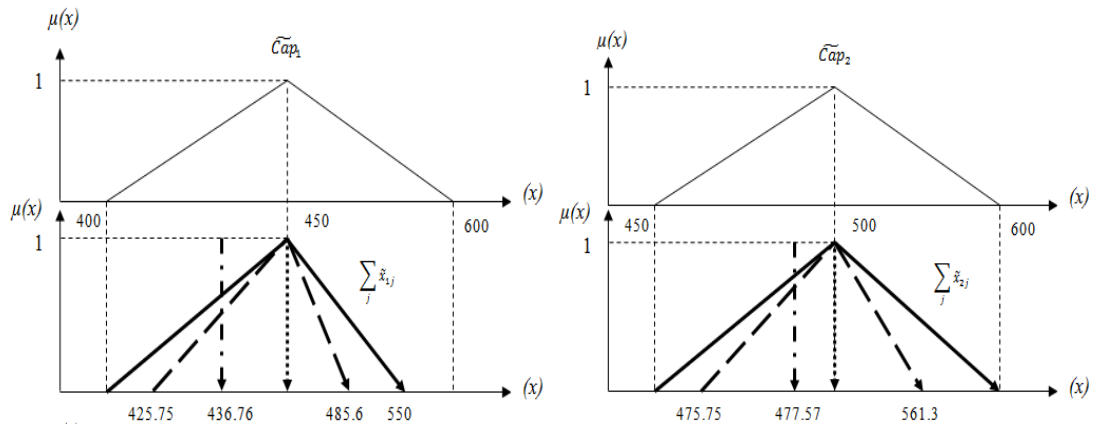


Figure 2.35 Membership functions for outgoing flows according to different Δ values (Type-4 FFTP)

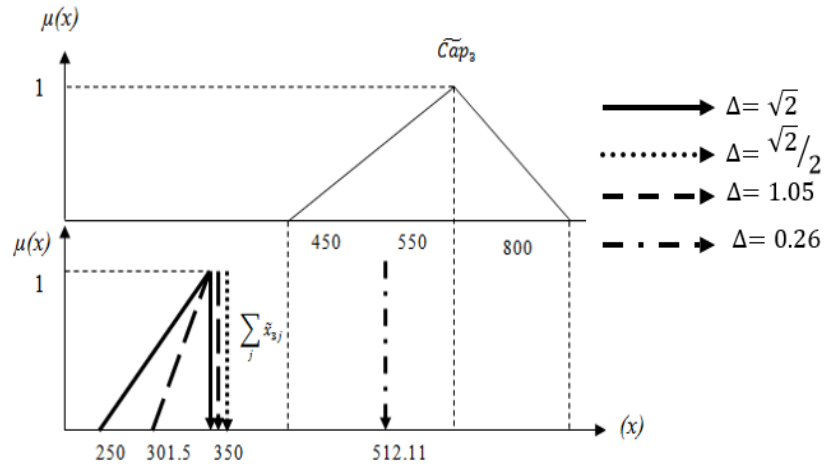


Figure 2.35 Membership functions for outgoing flows according to different Δ values (Cont.)

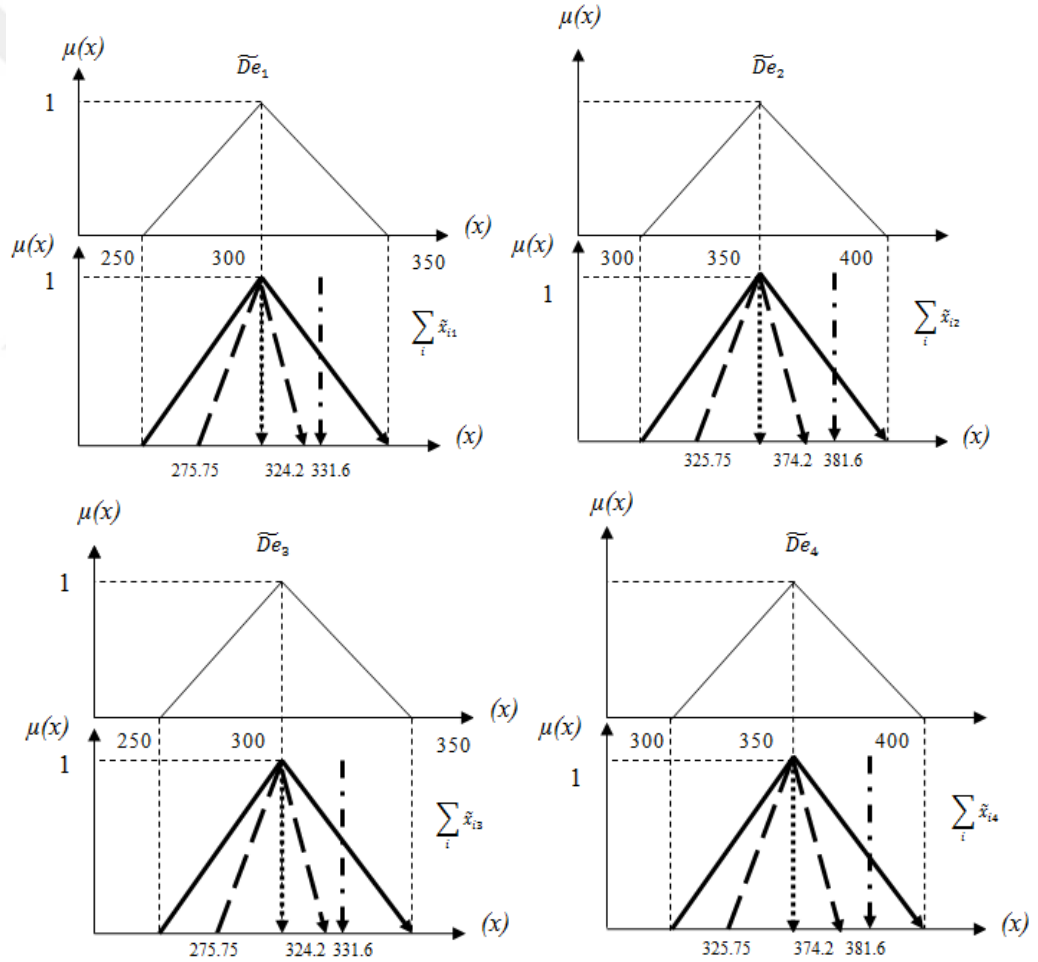


Figure 2.36 Membership functions for incoming flows according to different Δ values (Type-4 FFTP)

Actually, this means that there are feasible partially risk-free solutions for type-4 FFTPs for decision maker(s) whose risk-sensitivity degree is greater than 0.25.

It should be emphasized for this type of FFTPs that when the risk acceptance level is lower than $\Delta < \sqrt{2}/2$, the core values of the decision variables may differ from the core values of the capacities of the sources and/or demands of the destinations for $\alpha = 0$ level. Conversely, if the risk acceptance level is equal to or larger than $\Delta \geq \sqrt{2}/2$, the core values of the fuzzy decision variables will be fixed to the core values of the capacities of the sources and/or demands of the destinations. Moreover, with the usage of different risk acceptance levels, change of the membership function form for the fuzzy objective value is presented in Figure 2.37.

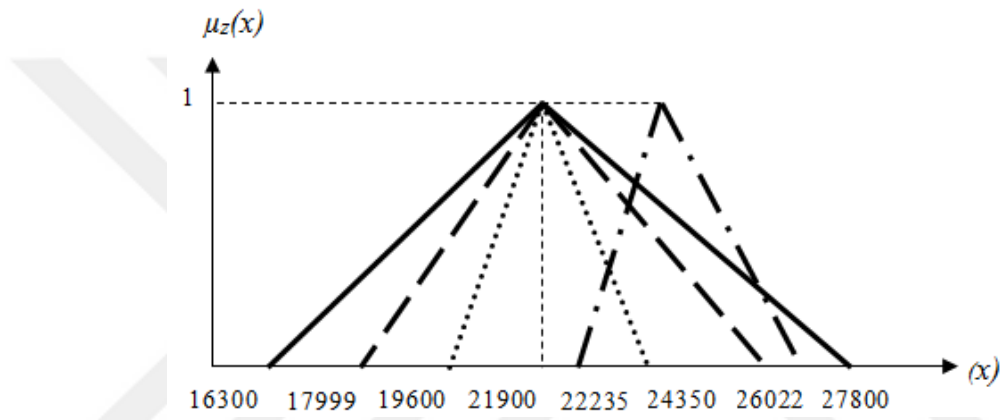


Figure 2.37 Membership functions of fuzzy objective function value for Type-4 FFTP

When type-5 FFTPs are transformed into the crisp form by utilizing the existing methods (Ezzati et al., 2015; Kaur & Kumar, 2011; Kumar et al., 2010 and 2011), it cannot be provided any feasible solution. The main reason is that these methods do not take into account the overlaps or intersections of the fuzzy numbers. Also, they do not depend on α -cuts. In fact, it is possible to obtain feasible but risky solutions for this type of problems below a specified α -level where the fuzzy total demands and fuzzy total capacities are intersected. Feasible fuzzy efficient solutions for FFTP example can only be obtained in the region *B* as depicted in Figure 2.38. Thus, the CFA operations should also be done for the α -levels which may produce feasible solutions.

For instance, the membership function of the linguistic term “*transportation quantity from the source-1 is approximately equal to the capacity of that source for less and equal to $\alpha = 3/8$ level*” is displayed in Figure 2.39. In order to achieve these

feasible but risky solutions by using the proposed CFA based method, the constraints of crisp LP model should be revised.

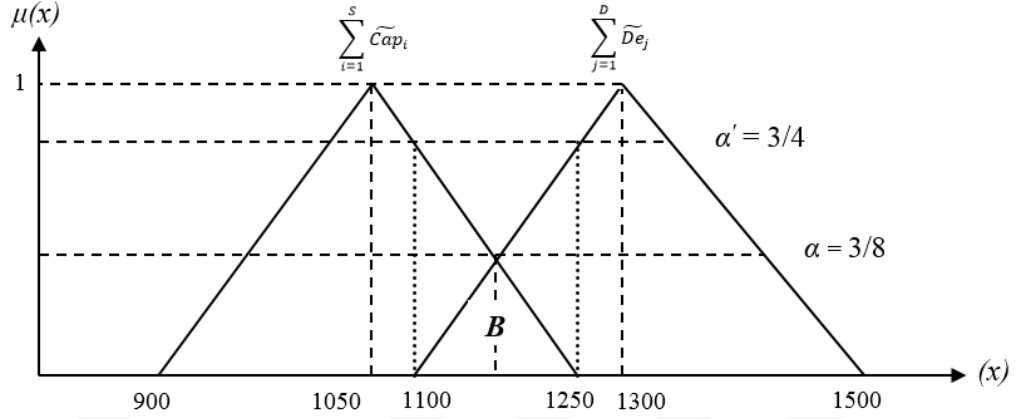


Figure 2.38 Membership functions of fuzzy total capacities and demands for Type-5 FFTP

This revision can be formulated as follows for the capacity constraint of source-1 and demand satisfaction constraint of destination-1 by considering the predetermined $\alpha = 3/8$ level and below:

$$[375 + 100\alpha] - \left(\sum_{j=1}^D x_{1j}^o - \left(\sum_{j=1}^D x_{1j}^o - \sum_{j=1}^D x_{1j}^m \right) \alpha \right) \geq -\Delta(100) \sqrt{2} (3/8 - \alpha) \quad (2.124)$$

$$[450 - 100\alpha] - \left(\sum_{j=1}^D x_{1j}^p + \left(\sum_{j=1}^D x_{1j}^m - \sum_{j=1}^D x_{1j}^p \right) \alpha \right) \geq \Delta(100) \sqrt{2} (3/8 - \alpha) \quad (2.125)$$

$$\left(\sum_{i=1}^S x_{i1}^o - \left(\sum_{i=1}^S x_{i1}^o - \sum_{i=1}^S x_{i1}^m \right) \alpha \right) - [250 + 50\alpha] \geq \Delta(50) \sqrt{2} (3/8 - \alpha) \quad (2.126)$$

$$\left(\sum_{i=1}^S x_{i1}^p + \left(\sum_{i=1}^S x_{i1}^m - \sum_{i=1}^S x_{i1}^p \right) \alpha \right) - [287.5 - 50\alpha] \geq -\Delta(50) \sqrt{2} (3/8 - \alpha) \quad (2.127)$$

where α represents the maximum α -cut level which one can obtain a feasible solution ($\alpha = 3/8$ in the numerical example). Moreover, α' in Figure 2.38 is the α -cut level where the total fuzzy capacities and total fuzzy demands are equal to the bounds of the feasible region B , i.e., 1100 and 1250 in the current numerical example. This α' level is utilized for determining the bounds of the constraints in the revised crisp LP model. Therefore, the revised LP model can generate feasible fuzzy efficient solutions for the α -cut levels that are less and equal to $3/8$. For the sake of simplicity, membership

functions of capacities and demands for each source/destination are shown in Figures 2.40 and 2.41, respectively.

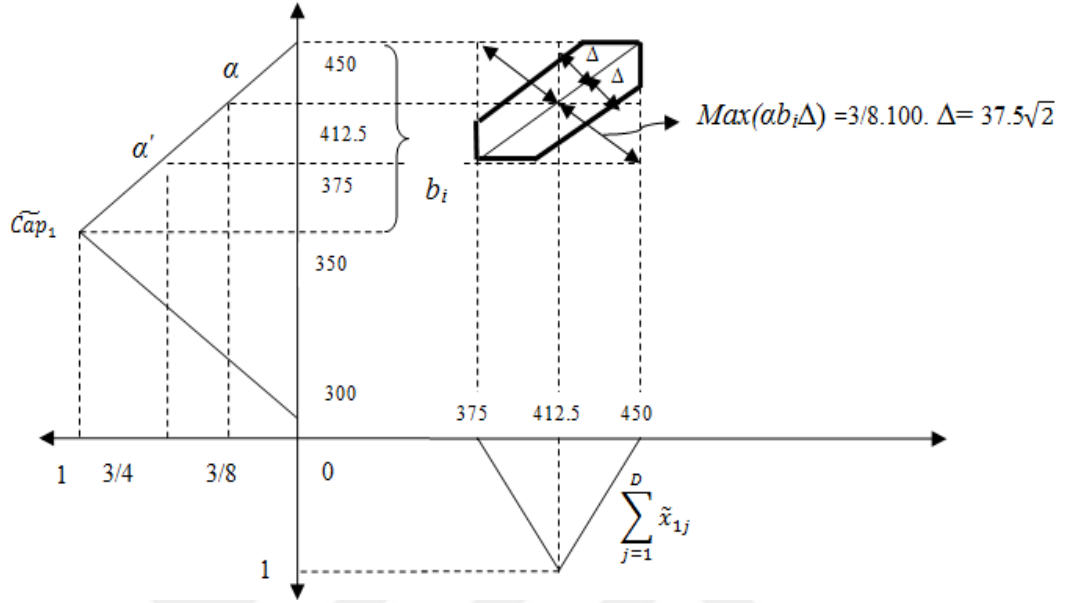


Figure 2.39 Membership function of the fuzzy relation “ $\sum_j x_{1j}$ is approximately equal to Cap_l ” for $\alpha \leq 3/8$ level

For the α -levels below $3/8$, the constraints’ bounds and the tolerance values should also be modified.

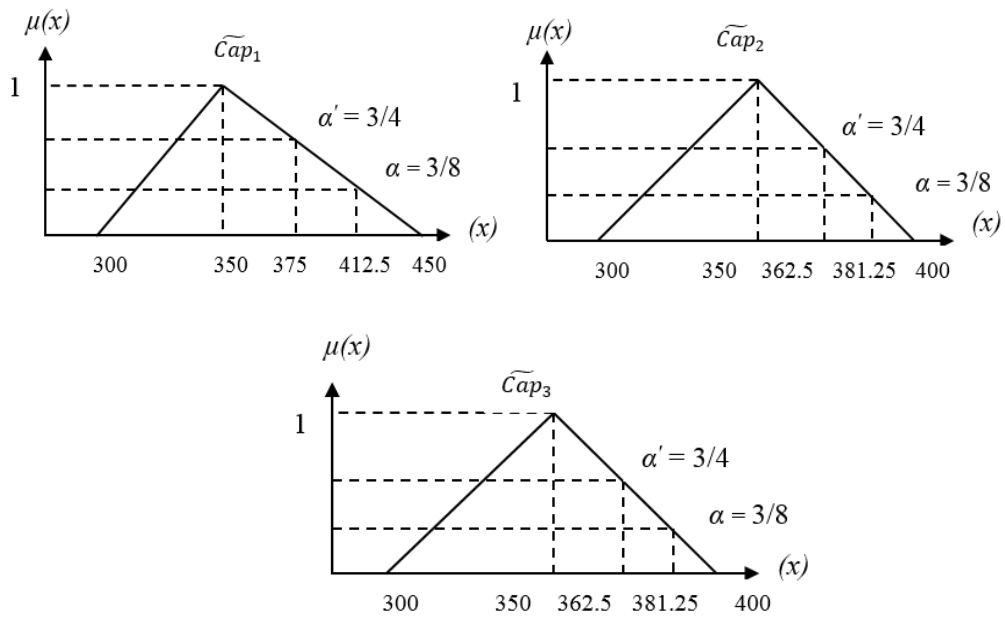


Figure 2.40 The individual membership functions of capacities for Type-5 FFTP

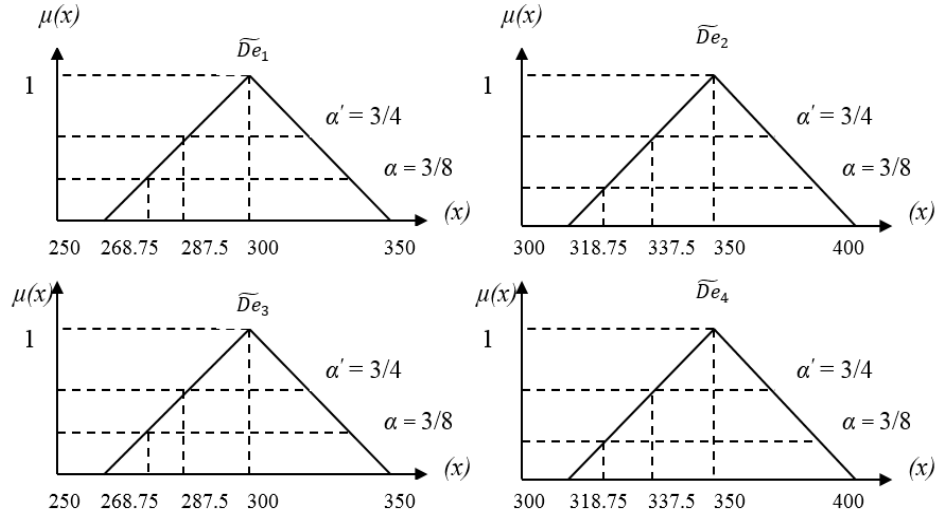


Figure 2.41 The individual membership functions of demands for Type-5 FFTP

For example, the constraints for source-1 and destination-1 can be updated as follows for the α -levels above 3/8:

$$[300 + 50\alpha] - \left(\sum_{j=1}^D x_{1j}^o - \left(\sum_{j=1}^D x_{1j}^o - \sum_{j=1}^D x_{1j}^m \right) \alpha \right) \geq -\Delta (75) \sqrt{2} (1 - \alpha) \quad (2.128)$$

$$[450 - 100\alpha] - \left(\sum_{j=1}^D x_{1j}^p + \left(\sum_{j=1}^D x_{1j}^m - \sum_{j=1}^D x_{1j}^p \right) \alpha \right) \geq \Delta (75) \sqrt{2} (1 - \alpha) \quad (2.129)$$

$$\left(\sum_{i=1}^S x_{i1}^o - \left(\sum_{i=1}^S x_{i1}^o - \sum_{i=1}^S x_{i1}^m \right) \alpha \right) - [250 + 50\alpha] \geq \Delta (50) \sqrt{2} (1 - \alpha) \quad (2.130)$$

$$\left(\sum_{i=1}^S x_{i1}^p + \left(\sum_{i=1}^S x_{i1}^m - \sum_{i=1}^S x_{i1}^p \right) \alpha \right) - [350 - 50\alpha] \geq -\Delta (50) \sqrt{2} (1 - \alpha) \quad (2.131)$$

The other capacity constraints and demand satisfaction constraints should also be modified similarly. Thereafter, when obtained crisp equivalent model for α -levels above 3/8 is solved, there is no feasible solution for any risk sensitivity degree. On the other hand, after solving the obtained crisp LP model for type-5 FFTP for α -cut levels below 3/8, the following fuzzy efficient solutions which are given in Table 2.14 can be provided. However, as mentioned previously, any feasible solution cannot be found for the risk-averse person and partially risk-averse decision makers whose risk sensitivity degree is lower than $\Delta < \sqrt{2}/2$. Fortunately, feasible and applicable solutions can be achieved for the risk-neutral and risk seekers.

Table 2.14 Fuzzy efficient solutions by proposed CFA based approaches for $\alpha \leq 3/8$ (Type-5 FFTP)

Sources/ Destinations	$\Delta = 0$ (Risk-averse)	$\Delta = 0.35$ (Partially risk-averse)	$\Delta = \sqrt{2}/2$ (Risk-neutral)	$\Delta = 1.05$ (Partially risk-seeker)	$\Delta = \sqrt{2}$ (Risk-seeker)
S1-D1	NA	NA	(268.75, 268.75, 268.75)	(259.6, 268.75, 277.84)	(250, 268.75, 287.5)
S1-D2	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S1-D3	NA	NA	(143.75, 143.75, 143.75)	(134.65, 143.75, 152.8)	(125, 143.75, 162.5)
S1-D4	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S2-D1	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S2-D2	NA	NA	(62.5, 62.5, 62.5)	(62.5, 62.5, 62.5)	(62.5, 62.5, 62.5)
S2-D3	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S2-D4	NA	NA	(318.75, 318.75, 318.75)	(309.65, 318.75, 327.8)	(300, 318.75, 337.5)
S3-D1	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S3-D2	NA	NA	(256.25, 256.25, 256.25)	(247.15, 256.25, 265.3)	(237.5, 256.25, 275)
S3-D3	NA	NA	(125, 125, 125)	(125, 125, 125)	(125, 125, 125)
S3-D4	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
Fuzzy Objective	Infeasible solution	Infeasible solution	(18093.75, 18874.2-21553.9, 22381.25)	(17539.1, 18874.2-21553.9, 23063.2)	(16950, 18874.2-21553.9, 23787.5)

The membership functions of the total outgoing flows from the sources and total incoming flows to the destinations are shown in Figures 2.42 and 2.43 for $\Delta \geq \sqrt{2}/2$ since there is no feasible solution below this risk sensitivity degree.

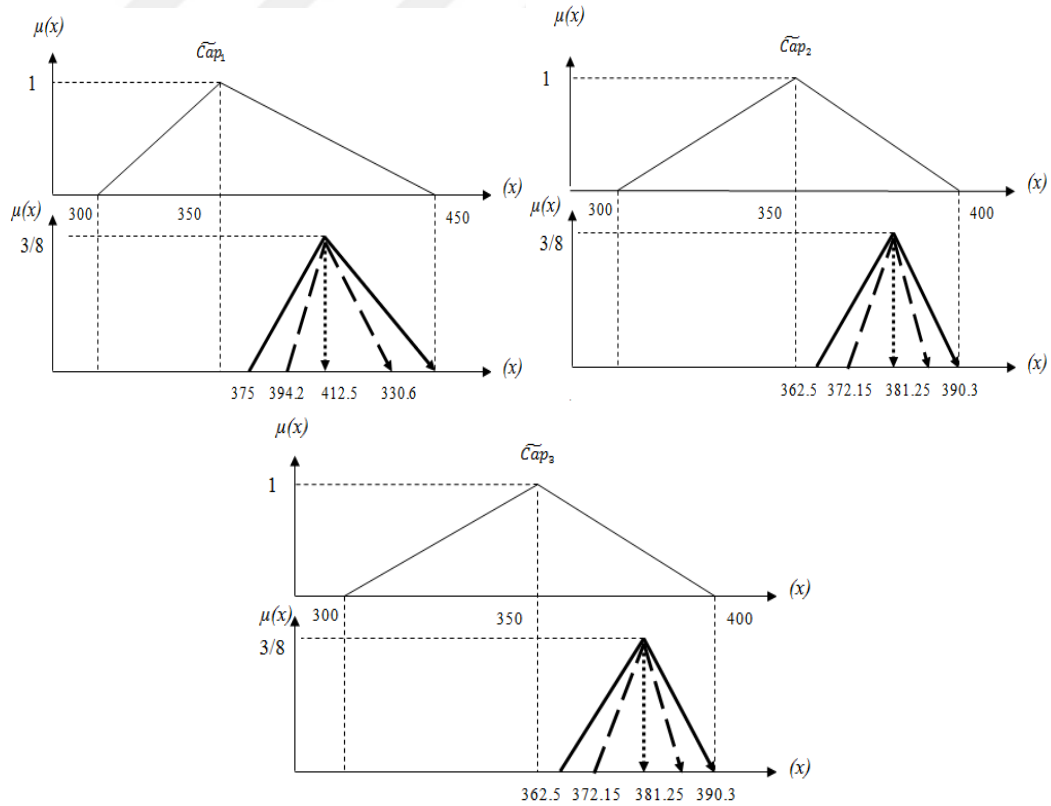


Figure 2.42 Membership functions for outgoing flows according to different Δ values (Type-5 FFTP)

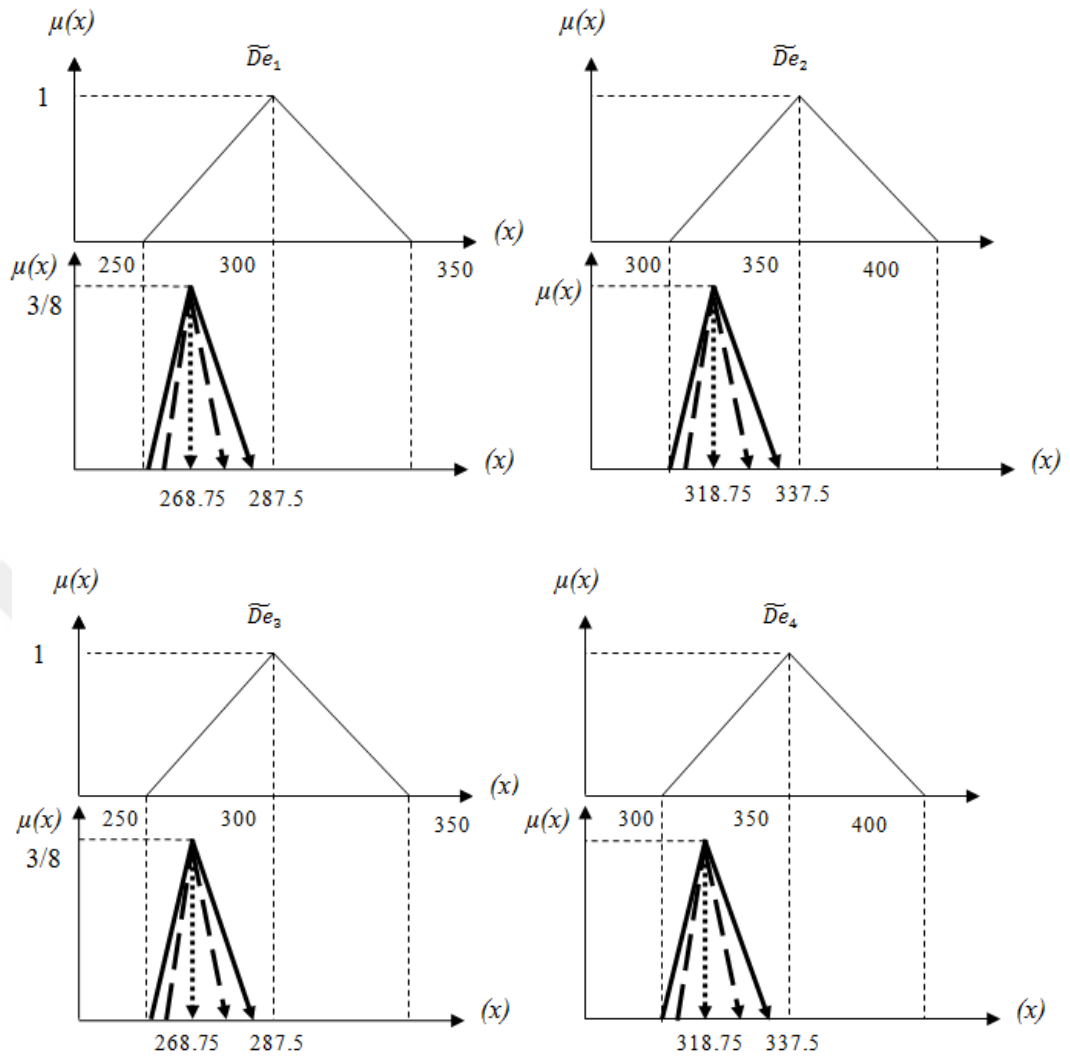


Figure 2.43 Membership functions for incoming flows according to different Δ values (Type-5 FFTP)

Furthermore, membership function for fuzzy objective value is presented in Figure 2.44 with different risk attitudes.

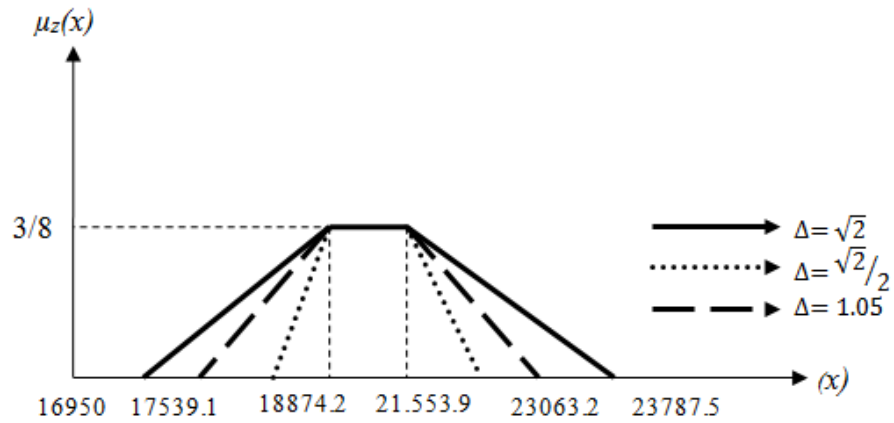


Figure 2.44 Membership function of fuzzy objective value for type-5 FFTP ($\alpha \leq 3/8$)

2.7.2 Comparisons with Methods Incorporating Crisp Decision Variables

In this sub-section, the previous numerical studies are also extended by making further comparisons with some of the well-known methods from the literature, which are also used to solve fuzzy transportation problems without utilizing fuzzy decision variables directly. Actually these methods are used to solve some fuzzy transportation problems which are the subset of the FFTPs studied in this chapter. It is aimed to present how the proposed CFA based approaches (which can handle the most generalized version of the fuzzy transportation problems) compares with relatively less generalized methods in terms of the model size and the solution characteristics.

The first comparison is made with the method of Liu and Kao (2004). They developed a method which is based on the extension principle in order to convert the fuzzy transportation problem into a pair of crisp mathematical programs. However, decision variables (transportation quantities) are assumed to be crisp in their method. Actually, some of the parameters such as cost coefficients, supply and demand quantities are taken as fuzzy numbers. Thus, this form of the fuzzy transportation problem can be seen as the subset of FFTPs. For this reason, it is assumed that the decision variables may take crisp values while testing their method on the different FFTPs given in Section 2.7.1. The results which are shown in Table 2.15 are obtained for type-1 FFTP via the method of Liu and Kao (2004).

Table 2.15 Solution of type-1 FFTP provided by the method of Liu and Kao (2004)

Sources/ Destinations	D1		D2		D3		D4	
	$\alpha = 0$	$\alpha = 1$	$\alpha = 0$	$\alpha = 1$	$\alpha = 0$	$\alpha = 1$	$\alpha = 0$	$\alpha = 1$
S1	6.2; 7.8	7	0; 0	0	1; 1	1	0; 0	0
S2	0; 0	0	0; 0	0	4.2; 5.8	5	7.8; 10.2	9
S3	0; 0	0	8.9; 11.1	10	1.3; 2.7	2	0; 0	0

The list of the α -cuts of the total transportation cost at different α values is given by Table 2.16. Moreover, membership function for fuzzy objective value is depicted in Figure 2.45. As it can be seen from this figure, Liu and Kao's (2004) method gave the same fuzzy objective value with our proposed CFA based approaches for a decision maker with risk-seeking characteristic ($\Delta = \sqrt{2}$).

Table 2.16 The α -cuts of total transportation cost for type-1 FFTP resulted from Liu and Kao (2004)

α	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
z_{α}^L	241.98	252.10	262.41	272.93	283.64	294.54	305.64	316.94	328.43	340.12	352
z_{α}^U	433.46	424.94	416.52	408.17	399.9	391.72	383.61	375.58	367.64	359.78	352

In contrast to the proposed approaches, that method presents crisp solutions for each α -cut level. Fortunately, our proposed approaches provide fuzzy intervals at different α values. When the results are compared, it can be clearly seen from Tables 2.15 and 2.16 that the obtained crisp solutions via the method of Liu and Kao (2004) constitute the bounds of our fuzzy efficient solutions. Additionally, one can achieve more precise solutions for relatively risk averse decision makers ($\Delta = 1$ or $\Delta = \sqrt{2}/2$) by utilizing the proposed CFA based approaches.

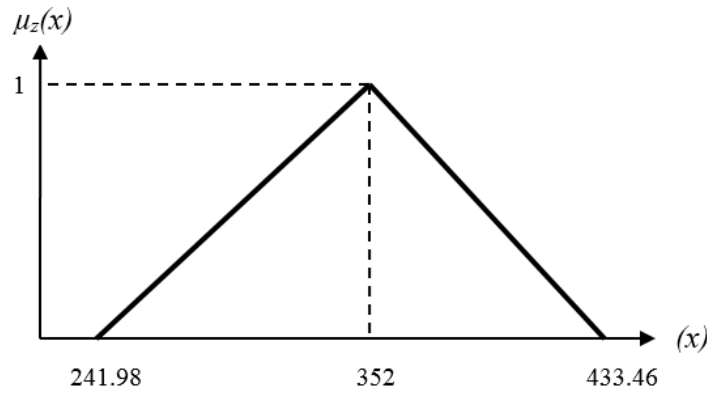


Figure 2.45 Membership function of fuzzy objective value for type-1 FFTP (Liu & Kao, 2004)

As mentioned previously, there is no feasible and applicable solution for type-2 FFTP at any α -cut level. Because, fuzzy total capacities are not sufficient to satisfy the fuzzy total demands. In detail, a fuzzy transportation problem is infeasible if the upper bound of the fuzzy total capacities is less than the lower bound of the fuzzy total demand (Liu & Kao, 2004).

For the type-3 FFTP, the results which are shown in Table 2.17 are yielded via the method of Liu and Kao (2004). Table 2.18 presents the list of the α -cuts of the total transportation cost at different α values. Additionally, membership function for the fuzzy objective value is shown in Figure 2.46. When the results are compared for this type of FFTP, Liu and Kao's (2004) fuzzy objective value already incorporates our proposed method's results of decision makers with different risk attitudes as depicted in Figure 2.46.

Table 2.17 Solution of type-3 FFTP provided by the method of Liu and Kao (2004)

Sources/ Destinations	D1		D2		D3		D4	
	$\alpha=0$	$\alpha=1$	$\alpha=0$	$\alpha=1$	$\alpha=0$	$\alpha=1$	$\alpha=0$	$\alpha=1$
S1	250; 200	300	0; 0	0	250; 350	300	0; 0	0
S2	0; 0	0	300; 150	350	0; 0	0	300; 400	350
S3	0; 150	0	0; 250	0	0; 0	0	0; 0	0

In detail, the upper value (28100) of our provided solution for a risk-averse decision maker ($\Delta=0$) is the same with Liu and Kao's (2004) objective value for $\alpha=0$ level ($Z_{\alpha=0}^U=28100$). Moreover, nearby objective values (14900 versus 15050) are achieved with the method of Liu and Kao's (2004) for the lower bound of $\alpha=0$ level in the case of decision maker is a risk seeker ($\Delta=\sqrt{2}$).

Table 2.18 The α -cuts of total transport cost for type-3 FFTP from method of (Liu and Kao, 2004)

α	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
z_{α}^L	14900	15373.5	15854	16341.5	16836	17337.5	17846	18361.5	18884	19413.5	19950
z_{α}^U	28100	27210.5	26332	25454.5	24608	23762	22928	22104	21302	20541	19950

Furthermore, it should be noted here that Liu and Kao's (2004) method gives the same solution with the proposed CFA based approaches for a risk-neutral decision maker ($\Delta=\sqrt{2}/2$) at $\alpha=1$ level. As it can be obviously seen from Figures 2.30 and 2.46, since results of Liu and Kao's (2004) method cover our all of the fuzzy efficient solutions for the decision makers with different risk attitudes, it can be concluded that proposed CFA based approaches are able to prevent overly imprecise solutions or over estimation in the fuzzy objective value.

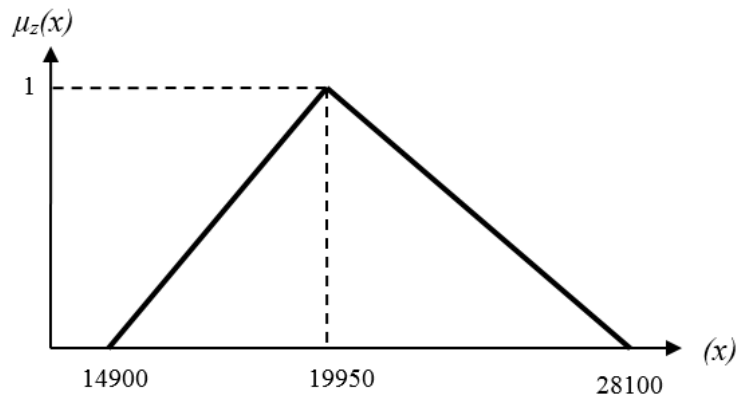


Figure 2.46 Membership function of objective value for type-3 FFTP (Liu & Kao, 2004)

When type-4 FFTP is solved via the method of Liu and Kao (2004), the results which are given in Table 2.19 are obtained. Similarly, α -cuts of the total transportation cost at different α values are listed on Table 2.20. Furthermore, membership function for fuzzy objective value is displayed in Figure 2.47. According to Figures 2.37 and 2.47, similar to the type-3 FFTP, Liu and Kao's (2004) fuzzy objective value contains the results of the proposed CFA based approaches for decision makers with different risk attitudes in type-4 FFTP.

Table 2.19 Solution of type-4 FFTP provided by the method of Liu and Kao (2004)

Sources/ Destinations	D1		D2		D3		D4	
	$\alpha=0$	$\alpha=1$	$\alpha=0$	$\alpha=1$	$\alpha=0$	$\alpha=1$	$\alpha=0$	$\alpha=1$
S1	250; 50	300	0; 0	0	150; 350	150	0; 0	0
S2	0; 0	0	150; 50	150	0; 0	0	300; 400	350
S3	0; 300	0	150; 350	200	100; 0	150	0; 0	0

Table 2.20 The α -cuts of transportation cost for type-4 FFTP from the method of Liu and Kao (2004)

α	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Z_{α}^L	16300	16828.5	17364	17906.5	18456	19012.5	19576	20146.5	20274	21308.5	21900
Z_{α}^U	29600	28785	27980	27185	26400	25625	24860	24105	23360	22625	21900

In fact, the lower bound (16300) of our provided solution for a risk-seeker ($\Delta = \sqrt{2}$) is the same with Liu and Kao's (2004) results for $\alpha = 0$ level ($Z_{\alpha=0}^L = 16300$). Fortunately, less costly solution (27800) is achieved by the proposed CFA based approaches than Liu and Kao's (2004) upper value (29600) of $\alpha = 0$ level when the decision maker is assumed to be a risk seeker ($\Delta = \sqrt{2}$). In addition, Liu and Kao's (2004) method gives the same solution (21900) with the proposed CFA based approaches for the decision makers namely risk-neutral, partially risk-seeker and risk seeker ($\Delta = \sqrt{2}/2, \Delta = 1.05, \Delta = \sqrt{2}$) at $\alpha = 1$ level.

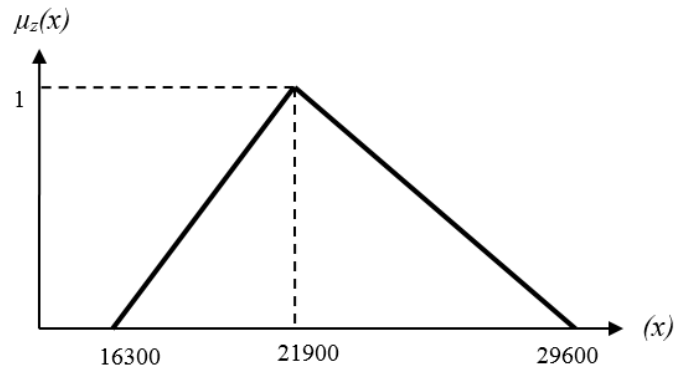


Figure 2.47 Membership function of fuzzy objective value for type-4 FFTP (Liu & Kao, 2004)

As it can be obviously seen from Figures 2.37 and 2.47 that more precise solutions can be yielded by the proposed CFA based solution approaches.

Liu and Kao's method (2004) gave the following results given in Table 2.21 for type-5 FFTP. In addition, list of the α -cuts of the total transportation cost at different α values are presented in Table 2.22. Similar to the proposed approaches, there are feasible solutions of this type of FFTP for the α -cut levels that are less and equal to $3/8$. Finally, membership function for fuzzy objective value is shown in Figure 2.48.

Table 2.21 Solution of type-5 FFTP provided by the method of Liu and Kao (2004)

Sources/ Destinations	D1		D2		D3		D4	
	$\alpha = 0$	$\alpha = 3/8$	$\alpha = 0$	$\alpha = 3/8$	$\alpha = 0$	$\alpha = 3/8$	$\alpha = 0$	$\alpha = 1$
S1	250; 150	268.75	0; 0	0	143.75; 300	143.75	0; 0	0
S2	0; 0	0	62.5; 100	62.5	0; 0	0	300; 300	318.75
S3	0; 200	0	237.5; 200	256.25	106.25; 0	125	0; 200	0

Table 2.22 The α -cuts of transportation cost for type-5 FFTP from the method of Liu and Kao (2004)

α	0.0	0.1	0.2	0.3	0.375	0.5	0.6	0.7	0.8	0.9	1.0
z_{α}^L	16856.2	17384.7	17920.2	18462.7	18874.2	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas
z_{α}^U	24150	23508.5	22836	22098.5	21553.9	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas

According to Figures 2.44 and 2.48, the proposed CFA based approaches presents the same results (18874.22 and 21553.91) with Liu and Kao's (2004) method at $\alpha = 3/8$ level. Additionally, nearby solutions are provided with this method for a risk seeker ($\Delta = \sqrt{2}$) at $\alpha = 0$ level (16856.25 versus 16950; 23787.5 versus 24150). In fact, Liu and Kao's (2004) method presented a fuzzy objective value with higher degree of uncertainty. As it is depicted in Figure 2.48, relatively more precise solutions can be provided by utilizing the proposed CFA based direct and indirect solution approaches.

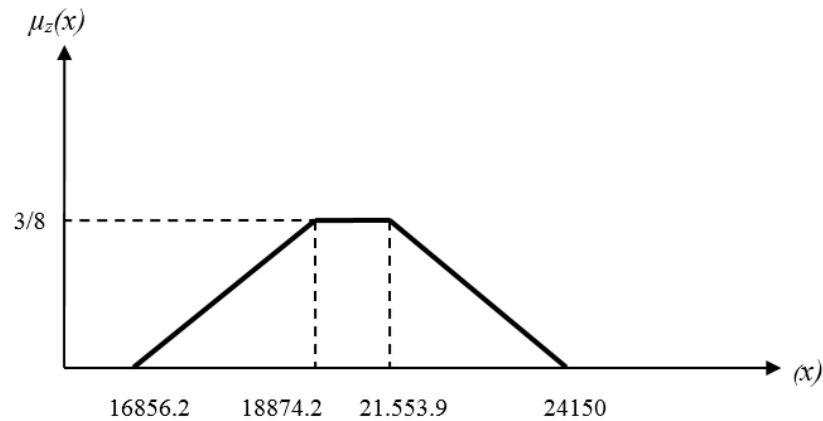


Figure 2.48 Membership function of fuzzy objective value for type-5 FFTP (Liu & Kao, 2004)

The other comparisons are made with the method of Jimenez and Verdegay (1998). They considered both interval and fuzzy solid transportation problems and proposed parametric programming approach in order to obtain fuzzy solutions to the fuzzy case. However, this method only takes into account the uncertainty or fuzziness embedded only in the constraint set. Actually, objective function coefficients were taken as crisp data in their method. Additionally, decision variables of the examined fuzzy transportation problem were also described as crisp values. In fact, they solved the stated fuzzy transportation problem under fuzzy equality constraints (fuzzy supplies and fuzzy demands). However, in this chapter, different types of FFTPs are formulated and solved under both fuzzy equality and fuzzy inequality constraints. For this reason, it is not an appropriate method to solve our FFTPs where the objective function coefficients are also represented by fuzzy numbers.

Fortunately, the proposed CFA based approaches can be utilized for solving this kind of fuzzy transportation problem with crisp cost parameters. Because, the given fuzzy transportation problem with crisp cost values is a subset of FFTP which is the main focus of this chapter. So, it can easily be solved by the proposed CFA based direct and indirect solution methodologies. For this reason, a numerical example on a fuzzy transportation problem which is given by Jimenez and Verdegay (1998) is solved by the proposed CFA based approaches in order to compare the results. Details of the examined fuzzy transportation problem with two sources and three destinations can be given as in Table 2.23.

Table 2.23 Data related to the numerical example given by Jimenez and Verdegay (1998)

Sources/ Destinations	Destination 1	Destination 2	Destination 3	Supplies
	Cost values			
Source 1	10	20	30	(5, 10, 15)
Source 2	20	50	60	(11, 16, 21)
Demands	(5, 10, 15)	(5, 9, 13)	(0, 1, 2)	

Firstly, the above fuzzy transportation problem was converted into an interval-parametric transportation problem. Then, the auxiliary parametric transportation problem was obtained by using the approach of Chanas et al. (1993). In contrast to the proposed CFA based transformation approach, the optimal solution of the auxiliary parametric transportation problem was not obtained from the solution of a converted crisp equivalent model of the fuzzy transportation problem. In fact, the optimal

solution of this auxiliary parametric transportation problem is provided by making use of the appropriate parametric algorithms of Srinivasan and Thompson (1972a) and (1972b). These are the main differences between the proposed CFA based approaches and Jimenez and Verdegay's approach (1998). Since the fuzzy cost values may not be considered by these parametric algorithms, the numerical examples of different types of FFTP's which are given in Section 2.7.1 are not solved by the method of Jimenez and Verdegay's approach (1998). The provided fuzzy solution to the above fuzzy transportation problem given in Table 2.23 can be presented by the following Tables 2.24 to 2.27:

Table 2.24 Solutions provided by the method of Jimenez and Verdegay (1998) for $r \in [0, 0.4]$

	Destination-1	Destination-2	Destination-3
Source-1	-	$5+4r$	r
Source-2	$11-5r$	-	-

Table 2.25 Solutions provided by the method of Jimenez and Verdegay (1998) for $r \in [0.4, \frac{2}{3}]$

	Destination-1	Destination-2	Destination-3
Source-1	-	$5+4r$	r
Source-2	$15-5r$	$-4+10r$	-

Table 2.26 Solutions provided by the method of Jimenez and Verdegay (1998) for $r \in [\frac{2}{3}, 0.7]$

	Destination-1	Destination-2	Destination-3
Source-1		$17-14r$	$-12+19r$
Source-2	$15-5r$	$-4+10r$	

Table 2.27 Solutions provided by the method of Jimenez and Verdegay (1998) with different r values

	Destination-1				Destination-2				Destination-3			
	$r = 0$	$r = 0.4$	$r = 2/3$	$r = 0.7$	$r = 0$	$r = 0.4$	$r = 2/3$	$r = 0.7$	$r = 0$	$r = 0.4$	$r = 2/3$	$r = 0.7$
Source-1	0	0	0	0	5	6.6	7.66	7.2	0	0.4	0.66	1.3
Source-2	11	13	11.66	11.5	0	0	2.66	3	0	0	0	0

Finally, list of the total transportation costs at different r values are presented in Table 2.28.

Table 2.28 Total transportation costs for the given example with different r values

r	0.0	0.1	0.2	0.3	0.4	0.5	2/3	0.7	0.8	0.9	1.0
Z_r	320	341	362	383	404	455	539.2	563	-	-	-

The previously given fuzzy transportation problem is also solved by utilizing the proposed CFA based approaches. Actually, the above problem corresponds to type-4 fuzzy transportation problem where fuzzy total demands are approximately less and equal than fuzzy total supplies. Similar to the method of Jimenez and Verdegay (1998), there is no feasible risk-free solution ($\Delta=0$) below $\alpha = 0.7$ level. Fortunately, one can provide realizable risk-free solutions for $\alpha \geq 0.7$ level. The obtained fuzzy efficient solutions for the given example by considering different risk acceptance levels of the decision maker(s) are presented in Table 2.29. Furthermore, with the usage of different risk acceptance levels, change of the membership function form for the fuzzy transportation cost is shown in Figure 2.49. According to Table 2.29, there are feasible and partially risk-free solutions for the given fuzzy transportation problem for the decision maker(s) whose risk-sensitivity degree is equal and greater than 0.5.

Table 2.29 Fuzzy efficient solutions of numerical example provided by CFA based approaches

Sources/ Destinations	$\Delta=0$ (Risk-averse)	$\Delta=0.26$ (Partially risk-averse)	$\Delta=0.5$ (Partially risk-averse)	$\Delta=\sqrt{2}/2$ (Risk-neutral)	$\Delta=1.05$ (Partially risk-seeker)	$\Delta=\sqrt{2}$ (Risk-seeker)
S1-D1	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S1-D2	NA	NA	(7.24, 7.24, 7.24)	(9, 9, 9)	(7.06, 9, 10.9)	(5, 9, 13)
S1-D3	NA	NA	(1.29, 1.29, 1.29)	(1, 1, 1)	(0.52, 1, 1.48)	(0, 1, 2)
S2-D1	NA	NA	(11.46, 11.46, 11.46)	(10, 10, 10)	(7.57, 10, 12.42)	(5, 10, 15)
S2-D2	NA	NA	(2.92, 2.92, 2.92)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
S2-D3	NA	NA	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
Fuzzy Objective	Infeasible solution	Infeasible solution	(559.4, 559.4, 559.4)	(410, 410, 410)	(308.2, 410, 511.8)	(200, 410, 620)

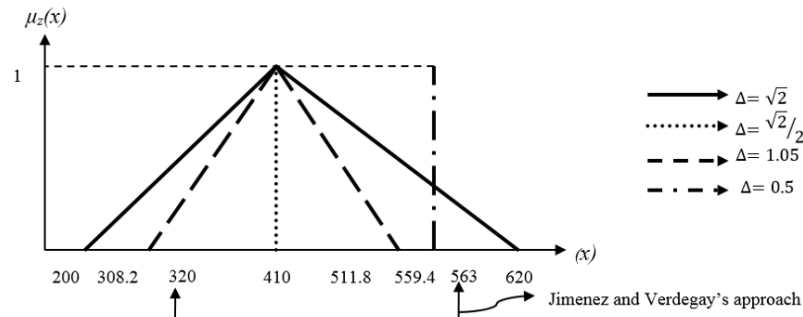


Figure 2.49 Membership functions of fuzzy objective value by proposed CFA based approaches

As it can be seen from the Tables 2.24 – 2.28 and Figure 2.49 that the provided solutions via proposed CFA based approaches contains all of the solutions obtained from the method of Jimenez and Verdegay (1998). It should also be emphasized here that most of the derived solutions by Jimenez and Verdegay (1998) constitute the bounds of fuzzy efficient solutions obtained from the proposed CFA based approaches.

2.7.3 Solution of A Fully Fuzzy Transshipment Problem via CFA based Approach

In addition to the previous extensive computational study for the different kinds of FFTPs, the proposed CFA based solution approaches are also used to solve a fully fuzzy transshipment problem. In the following, a numerical example on fully fuzzy transshipment problem is given involving three sources, four destinations and two transshipment points as demonstrated by Figure 2.50. The transportation costs, source capacities and demands are considered as fuzzy data in the example problem (Subulan & Baykasoğlu, 2015).

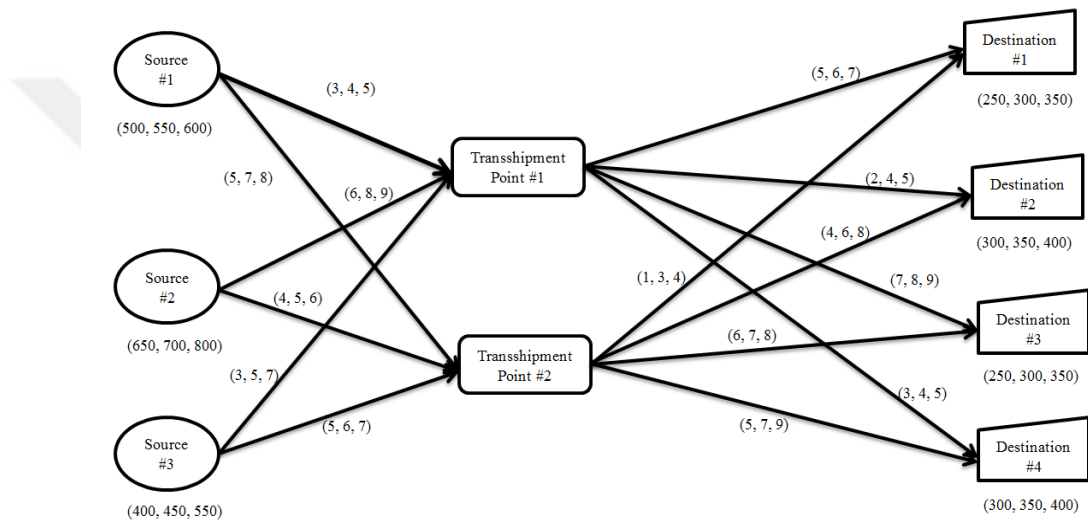


Figure 2.50 An illustrative example for fully fuzzy transshipment problem

The computational results of the proposed CFA based indirect solution approach are reported in Table 2.30. As it is obviously seen from these solutions, more precise and partially risk-free solutions can be generated in case of risk-aversion or value of Δ is decreased. However, the total transshipment cost value will increase in this situation. Alternatively, when the larger values of Δ which correspond to risk-seeking, it is possible to obtain lower cost values and more imprecise solutions as an expected result. But, the risks for capacity unavailability and unsatisfactory demand may increase.

The membership functions for the derived fuzzy solutions according to different risk attitudes can be given as in Figures 2.51 – 2.53. In detail, the first figure is the membership function of the total outgoing flows from a source. The second one is the membership functions of the incoming flows to a destination and the third one presents the membership degrees of both incoming and outgoing flows at a transshipment point.

Table 2.30 Fuzzy efficient solutions for fuzzy transshipment problem via proposed CFA based approach

Sources/ Destinations	$\Delta = 0$ Risk-averse	$\Delta = 0.35$ Partially Risk-averse	$\Delta = \sqrt{2}/2$ Risk-neutral	$\Delta = 1.05$ Partially Risk-seeker	$\Delta = \sqrt{2}$ Risk-seeker
S1-T1	(500,500,500)	(524.7,524.7,524.7)	(550,550,550)	(525.7,550,571.4)	(500,550,600)
S2-T2	(650,650,650)	(650.5,650.5,650.5)	(600,600,600)	(577.2,600,625.6)	(500,600,700)
S3-T1	(350,350,350)	(225.8,225.8,225.8)	(150,150,150)	(150,150,150)	(100,150,200)
T1-D2	(400,400,400)	(375.3,375.3,375.3)	(350,350,350)	(325.7,350,371.4)	(300,350,400)
T1-D3	(50,50,50)	-	-	-	-
T1-D4	(400,400,400)	(375.3,375.3,375.3)	(350,350,350)	(325.7,350,374.2)	(300,350,400)
T2-D1	(350,350,350)	(325.3,325.3,325.3)	(300,300,300)	(275.7,300,324.2)	(250,300,350)
T2-D2	-	-	-	(0, 0, 2.8)	-
T2-D3	(300,300,300)	(325.3,325.3,325.3)	(300,300,300)	(275.7,300,324.2)	(250,300,350)
Fuzzy Objective	(9650,13750,17100)	(9006.5,12734.8,15762.6)	(8350, 11750, 14500)	(7895.2, 11750.7,15302.7)	(7050,11750,16800)

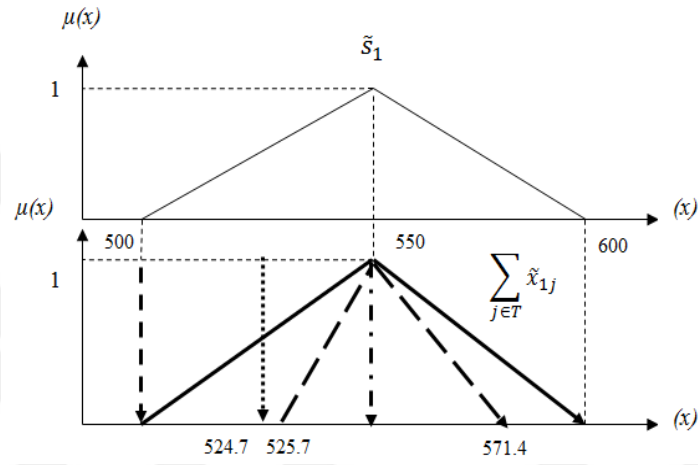


Figure 2.51 Membership functions of fuzzy total outgoing flows from source-1

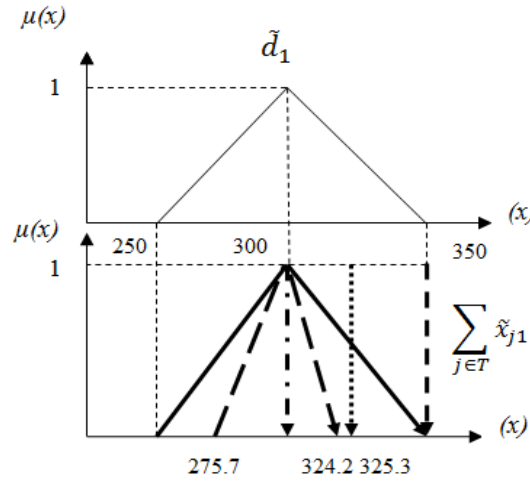


Figure 2.52 Membership functions of fuzzy total incoming flows to destination-1

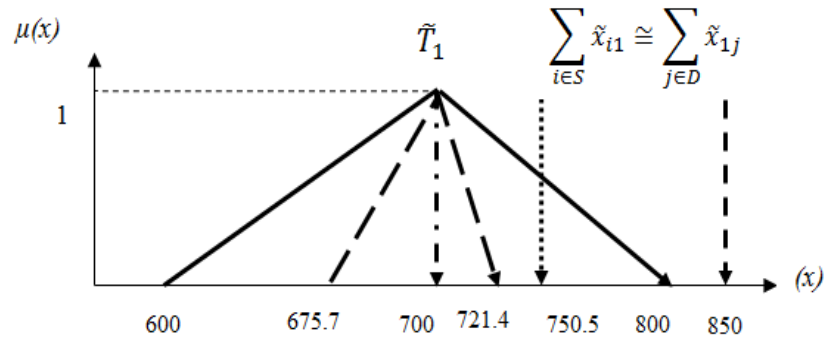


Figure 2.53 Membership functions of fuzzy incoming/outgoing flows from/to transshipment point-1

The fuzzy transportation and transshipment quantities obtained by the proposed CFA based approach for risk-seekers are also displayed by the following Figure 2.54.

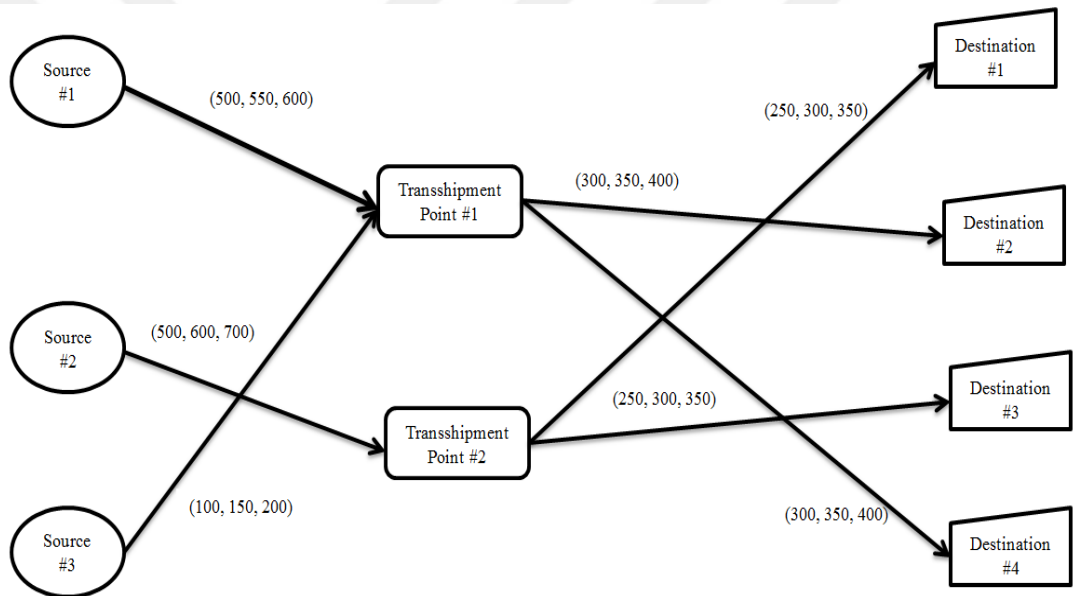


Figure 2.54 The fuzzy transportation and transshipment quantities in case of the risk seeking

Finally, the proposed CFA based approach is compared to different standard fuzzy arithmetic based solution methods from the literature in terms of computational efficiency and solution quality. In other words, in the scope of this section, the methods of Allahviranloo et al. (2008), Kumar et al. (2010) and (2011), Jayalakshmi and Pandian (2012) are selected from the literature in order to convert the examined fully fuzzy transshipment problem into the crisp equivalent form and compared with the proposed CFA based approach (Subulan & Baykasoğlu, 2015). The comparison results are also presented for the stated fully fuzzy transshipment problem as in the following Table 2.31.

Table 2.31 Summary of the results obtained from the different solution methodologies

FFTSP results	Deterministic	Allahviranloo et al.'s (2008) method	Kumar et al.'s method (2011)	Jayalakshmi & Pandian (2012)			Proposed CFA Based Method $\alpha = 0, \Delta = \sqrt{2}$
				Lower level	Middle level	Upper level	
Total number of variables	14	45	66	26	21	26	44
Total number of constraints	24	41	94	33	31	33	63
Total number of iterations	8	13	24	11	8	9	15
Total elapsed runtime	0.08	0.11	0.09	0.08	0.08	0.08	0.12
Objective value	11750	11533.3	11900	7300	11750	16800	23850
Fuzzy objective	-	(\$10585.8, \$12121, \$15328.5)	(\$7300, \$11750, \$16800)	(\$7300, \$11750, \$16800)			(\$7050, \$11750, \$16800)

The membership functions of the fuzzy objective value which is acquired by applying the different methods is given in Figure 2.55.

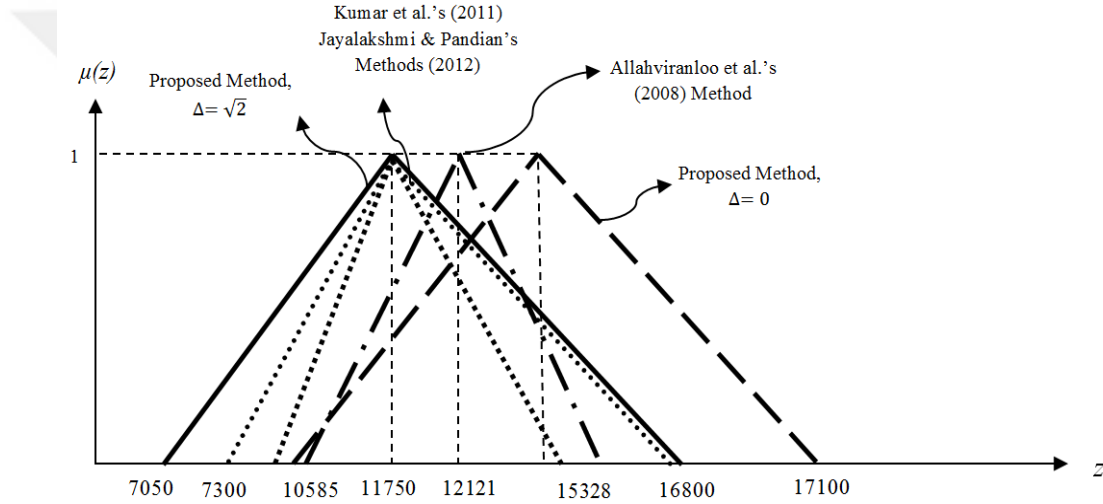


Figure 2.55 Membership functions of fuzzy transshipment cost value by different solution methods

According to computational results of comparative study, fuzzy efficient solutions which are provided by the proposed CFA based approaches are very similar with the existing methods' results for risk-seekers. On the contrary to these existing methods depending on standard fuzzy arithmetic, the proposed CFA based approaches are able to produce various fuzzy efficient solutions under different uncertainty levels and risk attitudes. It should also be highlighted here that, in all of the compared methods, the number of decision variables and constraints will increase reasonably after conversion of the fuzzy models into crisp equivalent forms. Correspondingly, the proposed indirect solution approach requires similar computational effort with the compared methods in the solution phase of the crisp LP models (Subulan & Baykasoğlu, 2015).

2.8 Chapter Summary

In the scope of this chapter, a novel direct and indirect solution approaches based on constrained fuzzy arithmetic concept are developed for solving fully fuzzy transportation and transshipment problems where all of the parameters and decision variables are stated as triangular fuzzy numbers. The proposed approaches also incorporate the decision maker's attitude toward risk. In fact, risk-free and/or risky solutions can be provided by utilizing the proposed approaches according to the risk sensitivity of decision maker. In order to obtain fuzzy efficient solutions for decision maker with various risk attitudes, fuzzy arithmetic operations are performed with the help of additional information. Actually, this information presents the requisite crisp or fuzzy constraints (relations) between the base variables of the fuzzy components in a fully fuzzy transportation environment. In the proposed direct solution approach, a constrained fuzzy arithmetic based decoding procedure with PSO algorithm is presented. In addition to constrained fuzzy arithmetic concept, the proposed fuzzy decoding procedure also incorporates a defuzzification technique for ranking fuzzy transportation costs and fuzzy fitness function values. Additionally, priority-based encoding method is used for solution representation of transportation networks. In order to find fuzzy efficient solutions, the proposed decoding procedure is embedded into PSO algorithm.

To illustrate the practicality and applicability of the proposed approaches, various types of fuzzy transportation and transshipment problems are solved and the obtained results are compared with the well-known methods in the literature. The solutions provided by the existing methods constitute the bounds of our fuzzy efficient solutions. Furthermore, computational results show that more reliable and information efficient solutions can be achieved for fuzzy transportation/transshipment problems by using the proposed approaches. Additionally, the decision maker(s) will be supported with yielding fuzzy efficient solutions under different uncertainty levels (α -cuts) and risk attitudes. In many real-life cases, providing a crisp solution is not easy since it is not possible due to the several uncertainties as discussed throughout this chapter. Therefore, it may always be desirable to provide fuzzy solutions by taking into consideration the decision maker's risk attitude in such occasions. Such a fuzzy

solution will provide possible outcomes with certain degree of memberships to the decision maker(s). This is especially useful for strategic decisions where more uncertainty may exist. Moreover, it is possible to generate crisp solutions from the provided fuzzy solutions by making use of any defuzzification method or some other auxiliary methods which fits the decision maker's purposes.

In the future works, the proposed direct solution approaches can be extended by solving large scaled fuzzy transportation problems including many transshipment nodes. It is also scheduled as a future work to model and solve fully fuzzy supply chain planning and logistics network design problems by utilizing the proposed CFA based direct and indirect solution approaches.



CHAPTER THREE

AN ANALYSIS OF FULLY FUZZY LINEAR PROGRAMMING WITH FUZZY DECISION VARIABLES THROUGH A REVERSE LOGISTICS NETWORK DESIGN PROBLEM

3.1 Chapter Introduction

In fuzzy mathematical programming literature, most of the solution approaches deal with the fuzziness related to the aspiration levels of the objective(s) and some model parameters, i.e., objective functions' coefficients, technological coefficients and right hand side values of the constraints. Because, available information on these parameters may not be precise and/or the decision maker(s) generally may not precisely know the values of these parameters. On the other hand, fully fuzzy linear programming (FFLP) problems in which all of the parameters and decision variables are stated as fuzzy numbers has been an attractive research topic for the researchers in recent years. However, literature on fuzzy mathematical programming with fuzzy decision variables is not rich as there are a few studies available on this research field. In fact, decision variables of a fuzzy mathematical program where all of the parameters are stated as fuzzy should also be considered as fuzzy numbers. Because, fuzzy characteristic of the decision may be partially lost and the decision making process may be limited with crisp solutions when the decision variables are considered as crisp real numbers (Baykasoğlu & Göçken, 2012). For this reason, instead of crisp solutions, obtaining fuzzy efficient solutions which provide ranges of flexibility to decision maker(s) may seem more impressive in fully uncertain environments (Hashemi et al., 2006). In other words, presenting the reasonable range of values for the decision variables can be comparatively better than the currently available crisp solutions (Sudhagar & Ganesan, 2010). In addition, fuzzy solutions may serve the regions containing potential satisfactory solutions around the optimal solutions to the decision maker(s). Thus, the final decisions can be made by the decision maker(s) as crisp ones. In other words, by taking the decision variables as fuzzy, choice of the crisp decisions among these fuzzy solutions will also be supported (Stanciulescu et al., 2003). Furthermore, it was emphasized by Xiaozhong et al. (1998) that it is possible to encounter some optimization problems such as the cardinality of optimal solutions and the number of

fairly superior solutions for a fuzzy linear program. Nevertheless, achieving the optimal solutions of a FFLP problem is a challenging task since there is no algorithm which determines the optimal values of the fuzzy decision variables exactly (Buckley & Feuring, 2000). In this chapter, a fully fuzzy reverse logistics (RL) network design problem whose parameters as well as the decision variables are taken as fuzzy numbers is discussed. Because, RL network design problems are generally surrounded by many uncertainties on quantity and timing of product returns, capacity of the recovery facilities, and disposal, recovery rates for the end-of-life products. Actually, these are the main factors contributed to the uncertainty in RL environments (Wang & Hsu, 2010). In other words, uncertainty in timing, quality and quantity of product returns are important aspects of RL network design problems. In a more detailed manner, the decision variables of a fully fuzzy RL network design problem should also be stated as fuzzy numbers because of the following reasons:

- There are two important sources of uncertainty related to the collection process in a RL network design problem. The first one is the uncertainty embedded into the quantity of returned products from the customer zones to the collection centers and the second one is the capacity of collection/inspection centers. Moreover, uncertain amounts of the collected products may be lost or perished because of the several reasons during the transportation operations. Thus, the collection quantities should be stated as fuzzy decision variables in a RL network design model.
- Similarly, decision variables regarding the quantities of recyclable and disposal products should also be defined as fuzzy due to the uncertainties of disposal rate, conformity/acceptance ratio, recycling and disposal capacities.
- Finally, amounts of recycled materials/components should also be taken as fuzzy decision variables since including some sort of ambiguity on the recovery rates.
- Since the outputs of any stage in a RL network constitutes the inputs of consecutive stages, fuzziness in one of the decision variables will also cause uncertainty into the other decision variables of latter stages. For instance, if the collection quantities are defined as fuzzy, the amounts of recyclable and disposed products should also be stated as fuzzy. Because, the output of the collection stage will be used as inputs in the recovery and disposal stages.

Therefore, the decision variables of these stages inherently contain uncertainty in nature. Furthermore, while realizing the design of a real-life RL network, it may be possible to perform a lot of revisions for the product flow quantities between the different network stages due to the fully uncertain environment and dynamism. For these reasons, producing fuzzy efficient solutions at first will be more appropriate for the decision maker(s) by taking the decision variables, i.e., distribution, collection, recycling and disposal amounts as fuzzy. Besides, the objective function value of a FFLP problem will also be fuzzy in nature since it is composed of various fuzzy decision variables and fuzzy cost coefficients. Thus, the decision maker(s) can easily recognize the changes in the objective value when these decision variables took different crisp values. In other words, decision maker(s) can maintain an opinion about range of the objective value.

This chapter presents a new parametric method which is able to generate fuzzy efficient solutions for FFLP problems under different uncertainty levels and risk tolerances. Therefore, risk-free and more reliable solutions can be provided according to the attitude of decision maker(s) toward risk. Moreover, since the proposed method is based on α -cuts (it is an alpha parametric model), it is possible to consider/model risk tolerances under various uncertainty levels. The performance of the proposed method is tested on a generic RL network design model whose parameters and decision variables (excluding the binary variables for opening of the potential collection centers and recycling facilities) are taken as fuzzy numbers. In order to show usefulness, validity and practicality of the proposed method, comparative analyses are conducted with the existing methods in the literature. The generalized closed-form mathematical representations of the crisp equivalent RL network design model which is transformed by using these methods are also given.

The rest of this chapter is organized as follows. A comprehensive literature review on FFLP problems and regarding classification are presented in Section 3.2. The details of fully fuzzy RL network design problem with notations, model assumptions and mathematical formulation are described in Section 3.3. A priority-based seeker optimization algorithm (SOA) including a decoding mechanism is presented for solution of the deterministic RL network design problem in Section 3.4. The

fundamentals of the proposed method and the comparative methods for FFLP problems are introduced in Section 3.5. This section also includes the crisp equivalent forms of the examined fully fuzzy RL network design model which is transformed by using these methods. In Section 3.6, an illustrative case study is presented for the solution of a hypothetical fully fuzzy RL network design problem with extensive comparisons. Finally, conclusions and discussions are presented in Section 3.7.

3.2 Literature Review on Linear Programming with Fuzzy Decision Variables

The concept of fuzzy mathematical programming with fuzzy decision variables was first introduced by Tanaka and Asia (1984). They provided the fuzzy solution of a FLP problem with fuzzy satisfaction criteria and fuzzy right hand side values via maximizing the possibility distributions of the fuzzy decision variables. Xiaozhong (1997) obtained the fuzzy optimal solution of a multi-objective FLP problem with fuzzy constraints and variables based on multiple objective optimization and two-stage method. Maleki et al. (2000) proposed a method based on the concept of comparing fuzzy numbers. Buckley and Feuring (2000) proposed a direct search technique by employing an evolutionary algorithm to solve FFLP problems. In their approach, they first transformed the FFLP model into a multi-objective optimization model. Then, an evolutionary algorithm was designed to find non-dominated solutions.

Liu and Liu (2002) utilized fuzzy simulation technique in order to evaluate the expected value of a fuzzy variable based on the credibility measure. Stanciulescu et al. (2003) proposed a method which uses fuzzy decision variables with a joint membership function. In that method, the lower boundaries of the decision variables were considered at first. Then, the proposed method was extended to achieve the lower and upper bounded fuzzy variables. Defuzzification of the objectives and constraints were carried out by making use of area compensation method and a worst case approach, respectively. Solution of the crisp equivalent model was provided by an interactive and iterative MAUT method. A two-phase method was developed by Hashemi et al. (2006) for solving FFLP problems where all of the parameters and decision variables are described as symmetric fuzzy numbers. Maximizing the possibilistic mean value of the objective function was achieved in the first phase. Then,

the standard deviation of the original fuzzy objective function was minimized by using the basic feasible solutions obtained from the first phase.

A ranking procedure which depends on total ordering of fuzzy numbers which utilizes non-algebraic numbers was proposed by Ghatee and Hashemi (2007) for solving fully fuzzified minimal cost flow problem. Mahdavi-Amiri and Nasseri (2007) introduced a new dual algorithm for direct solution of the fuzzy linear programming problems with the help of duality results and primal simplex tableau. On the other hand, their algorithm is able to solve linear programming problems in which decision variables, right hand side values of the constraints and aspiration levels of the objectives are defined as trapezoidal fuzzy numbers. A FFLP problem was transformed into the two crisp LP problems by Lotfi et al. (2009) that are maximization problem for the core and minimization problem for the margin. The proposed method is not an exact one, just an approximation technique since it relies on the approximation of the fuzzy numbers to the nearest symmetric triangular fuzzy numbers. Ghazanfari et al. (2009) developed a new method depending on the weak comparison rule which is one of the fuzzy ranking technique to solve time-cost trade-off problem in project scheduling. The decision variables of their time-cost trade-off model, i.e., activity durations and occurrence time of events, were taken as fuzzy and are assumed that they followed a triangular possibility distribution. Ebrahimnejad et al. (2010) proposed a fuzzy primal-dual algorithm by using a linear ranking function and duality results. However, the technological coefficients of the constraints are taken as crisp values in their numerical study. Baykasoglu and Göçken (2012) developed a direct solution approach for solving fuzzy mathematical programming problems with fuzzy decision variables based on integrating a fuzzy ranking method into a meta-heuristic algorithm namely particle swarm optimization which aims to rank the objective function values and determine the feasibility degrees of the constraints. The efficiency of their method was also tested on a product mix problem. Kaur and Kumar (2013) proposed a method for product of unrestricted L-R flat fuzzy numbers. Then, by using the proposed product operation, a new method namely Mehar's method is developed for solving FFLP problems which cannot be solved through any other existing methods. Ezzati et al. (2015) proposed a solution algorithm for FFLP problems by using a multiple objective optimization technique. In detail, the FFLP problem is converted into a

multi-objective linear program with three crisp objective functions based on a new lexicographic ordering on triangular fuzzy numbers. Then, the lexicographic method was utilized to obtain a lexicographic optimal solution which can be seen as an exact optimal solution of a FFLP problem. Baykasoğlu and Subulan (2015) proposed a parametric solution method which is mainly based on α -cut representation of fuzzy intervals for solving fuzzy linear programming models including fuzzy decision variables. They presented various fuzzy solutions for a fully fuzzy reverse logistics network design problem under different uncertainty levels and risk tolerances. In fact, more realizable, reliable and information efficient solutions can be achieved by making use of their method according to the decision maker's attitude toward risk.

In the scope of this chapter, the methods of Allahviranloo et al. (2008), Kumar et al. (2010), Kumar et al. (2011) and Jayalakshmi and Pandian (2012) are selected from the literature in order to transform the examined fully fuzzy RL network design model into the crisp equivalent form and compared with the proposed method. The main reasons to select these methods for comparison can be explained as follows:

- The method of Allahviranloo et al. (2008) provides an approximate solution to the FFLP problems. Hence, the comparison of exact and approximate solution methods for FFLP problems is intended,
- All of the selected methods are able to solve FFLP problems including both equality and inequality constraints. They are also applicable to FFLP problems involving negative elements into the coefficient matrix,
- All of these methods can be used to solve FFLP problems where fuzzy decision variables are defined by integer and continuous bounds,
- It is also aimed to compare methods of Allahviranloo et al. (2008) and Kumar et al. (2010) and (2011) which utilize fuzzy ranking functions and auxiliary variables within a transformation process with method of Jayalakshmi and Pandian (2012) which doesn't need any ranking function or auxiliary variable.

The classes of the fuzzy mathematical programs with fuzzy decision variables with respect to the fuzzy components, solution methodologies, types of constraints and used fuzzy numbers are summarized in Table 3.1.

Table 3.1 Classification of fuzzy mathematical programs with fuzzy decision variables

Article	Fuzzy terms				Constraint type		Type of the used fuzzy number				Solution methodology		
	Objective (s)	Coefficients of the objective(s)	Right hand side of the constraints	Coefficients of the constraints	Decision variables Integer Continuous	Equality	Inequality	Triangular	Trapezoidal	Symmetric fuzzy number	L-R flat fuzzy number	Direct	Transformation method
Xiaozhong (1997)	✓		✓				✓	✓					✓
Xiaozhong et al. (1998)	✓	✓	✓	✓			✓	✓					✓
Buckley & Feuring (2000)	✓	✓	✓	✓			✓	✓				✓	
Tanaka et al. (2000)	✓		✓				✓	✓					✓
Maleki et al. (2000)	✓		✓				✓		✓				✓
Stanculescu et al. (2003)		✓	✓	✓		✓	✓				✓		✓
Tsakiris & Spiliotis (2004)	✓		✓				✓	✓					✓
Hashemi et al. (2006)	✓	✓	✓	✓			✓			✓			✓
Ganesan et al. (2006)	✓	✓	✓				✓		✓			✓	✓
Aliev et al. (2007)	✓		✓	✓		✓	✓	✓				✓	
Amiri & Nasser (2007)	✓		✓				✓		✓			✓	
Allahviranloo et al. (2007)	✓		✓		✓	✓		✓					✓
Ghatee & Hashemi (2007)	✓	✓	✓			✓		✓					✓
Allahviranloo et al. (2008)	✓	✓	✓	✓			✓	✓					✓
Nasser (2008)	✓		✓				✓	✓					✓
Lotfi et al. (2009)	✓	✓	✓	✓		✓		✓					✓
Gani et al. (2009)	✓	✓	✓	✓			✓	✓				✓	
Stanojevic et al. (2009)	✓	✓	✓	✓			✓		✓				✓
Sudhagar & Ganesan (2010)	✓		✓		✓		✓	✓					✓
Pandian et al. (2010)	✓		✓		✓		✓	✓					✓
Ebrahimnejad et al. (2010)	✓		✓			✓	✓		✓			✓	
Kumar et al. (2010)	✓	✓	✓	✓		✓	✓	✓					✓
Kumar et al. (2011)	✓	✓	✓	✓		✓	✓	✓					✓
Kumar & Kaur (2011)	✓	✓	✓	✓			✓		✓				✓
Ahmad et al. (2011)	✓	✓	✓	✓			✓	✓				✓	
Kumar & Singh (2012)	✓	✓	✓	✓		✓			✓		✓		✓
Jayalakshmi et al. (2012)	✓	✓	✓	✓		✓	✓	✓					✓
Baykasoğlu et al. (2012)	✓	✓	✓	✓		✓	✓	✓				✓	
Sharma & Dubey (2012)	✓	✓	✓	✓		✓	✓		✓				✓
Beaula et al. (2012)	✓	✓	✓	✓		✓	✓	✓				✓	
Roseline et al. (2012)	✓	✓	✓			✓	✓		✓			✓	
Kaur & Kumar (2013)	✓	✓	✓	✓		✓	✓				✓		✓
The Proposed Method	✓	✓	✓	✓		✓	✓	✓					✓

3.3 Fully Fuzzy Reverse Logistics Network Design (FFRLND) Problem

3.3.1 Problem Description and Nomenclature

The RL network discussed in this chapter is a multi-echelon reverse supply chain consisting of customer zones, collection/inspection centers and disposal sites, recycling facilities, manufacturing plants with limited fuzzy capacities. As it can be seen from Figure 3.1 that reverse flows start with the collection of the used products from the different customer zones. After quality inspection at the collection centers, they are divided into recyclable products and scrapped products. Recyclable products are transferred to recycling facilities whereas the remaining fraction of collected products is disposed of at the disposal sites. In addition, collected end-of-life products which have good quality for recycling process are disassembled and processed until they become materials or components. When these products have been disassembled, materials/components are cleaned and tested. Recycling processes are performed on the materials to provide them with the same condition as the new ones. Obtained ‘new’ materials via the recycling process are transported to manufacturing plants and used for producing new products.

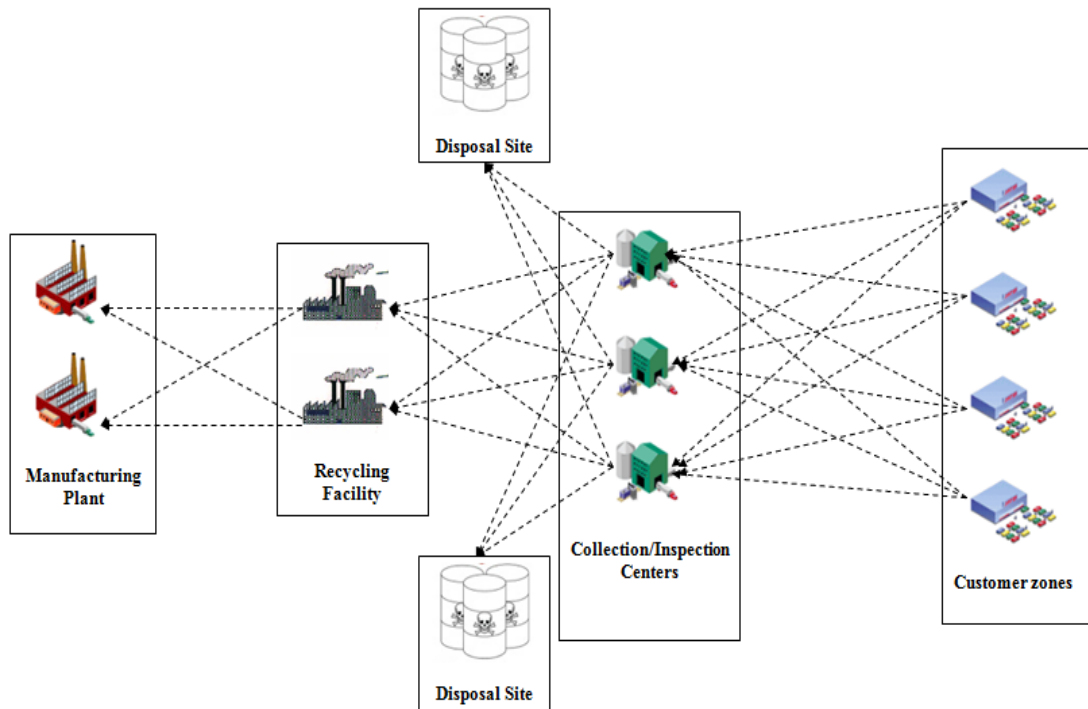


Figure 3.1 A generic form of the discussed reverse logistics network design problem

In order to formulate the previously mentioned RL network design problem as a fully fuzzy linear program, the indices, parameters and decision variables are defined in Table 3.2.

Table 3.2 Summary of the network notation, model parameters and decision variables

<i>Indices and sets:</i>	
i	set of the potential locations for collection/inspection centers; $i \in I$
j	set of the potential locations for recycling facilities; $j \in J$
l	fixed set of locations for customer zones; $l \in L$
k	fixed set of locations for disposal sites; $k \in K$
m	fixed set of locations for manufacturing plants; $m \in M$
<i>Fuzzy parameters:</i>	
$\widetilde{Re}_l$	amounts of returned products from customer zone l
$\widetilde{\gamma}$	fraction of disposed products through incineration or landfilling
$\widetilde{we}$	weight of the returned product
$\widetilde{cont}$	percentage of contribution of material/component obtained from one unit of returned product
$\widetilde{\alpha}_j$	recovery fraction or recycling rate at the recycling facility j
$\widetilde{f1}_i$	fixed opening and operating cost of the collection/inspection center i
$\widetilde{f2}_j$	fixed opening and operating cost of the recycling facility j
$\widetilde{c1}_{li}$	unit transportation cost of the returned product from customer zone l to collection/inspection center i
$\widetilde{c2}_{ij}$	unit transportation cost of the recyclable product from collection/inspection center i to recycling facility j
$\widetilde{c3}_{ik}$	unit transportation cost of the scrapped product from collection/inspection center i to disposal site k
$\widetilde{c4}_{jm}$	transportation cost for one kg of the recycled material/component from recycling facility j to manufacturing plant m
$\widetilde{Cap1}_i$	collection capacity of the collection/inspection center i
$\widetilde{Cap2}_j$	recovery capacity of the recycling facility j
$\widetilde{Cap3}_k$	disposal capacity of the disposal site k
$\widetilde{Cap4}_m$	warehousing capacity of the manufacturing plant m for materials/components
M	an arbitrary set large positive number
<i>Fuzzy decision variables:</i>	
$\widetilde{x}_{li}$	quantity of returned products shipped to collection center i from customer zone l
$\widetilde{z}_{ij}$	quantity of recyclable products shipped to recycling facility j from collection center i
$\widetilde{w}_{ik}$	quantity of scrapped products shipped disposal site k from collection/inspection center i
$\widetilde{v}_{jm}$	amounts of recycled material shipped to manufacturing plant m from recycling facility j
<i>Binary variables:</i>	
$y1_i$	1, If a collection center is opened at location i ; 0, otherwise
$y2_j$	1, If a recycling facility is opened at location j ; 0 otherwise

3.3.2 Modelling Assumptions

- The problem mentioned in this chapter is a single objective, single product, single period and multi-echelon RL network design problem with fuzzy parameters and fuzzy decision variables.
- In the proposed model, it is assumed that only one type of material can be recycled from the relevant product.
- The returned products that are not in the appropriate condition for recycling will be disposed after the inspection process. Besides, quantities of recyclable and scrapped products present uncertain fractions of total returned products from the customer zones.
- Shortages and inventory holding of the returned products and recycled materials are not allowable because of the single period consideration.
- Recovery rates may differ from one recycling facility to another according to the used recycling technology level.

3.3.3 Fully Fuzzy Linear Programming Formulation of the Problem

The main purpose of the present FFRLND model is to determine the locations and the numbers of collection centers and recycling facilities to be opened and the product/material flows between the different locations on the logistics network under fully uncertainty. The fuzzy objective of the proposed model is shown in (3.1) which is used to minimize the overall cost of the RL system including opening and operating costs of the collection/inspection centers, recycling facilities and the transportation costs between the different stages in the network.

$$\begin{aligned}
 \text{Minimize } \tilde{z} \cong & \sum_{i=1}^I \tilde{f}1_i \cdot y1_i + \sum_{j=1}^J \tilde{f}2_j \cdot y2_j + \sum_{l=1}^L \sum_{i=1}^I \tilde{c}1_{li} \cdot \tilde{x}_{li} \\
 & + \sum_{i=1}^I \sum_{j=1}^J \tilde{c}2_{ij} \cdot \tilde{z}_{ij} + \sum_{i=1}^I \sum_{k=1}^K \tilde{c}3_{ik} \cdot \tilde{w}_{ik} + \sum_{j=1}^J \sum_{m=1}^M \tilde{c}4_{jm} \cdot \tilde{v}_{jm}
 \end{aligned} \tag{3.1}$$

The constraints of the stated FFRLND model are expressed by Equations (3.2) to (3.12) as follows:

$$\sum_{i=1}^I \tilde{x}_{li} \geq \widetilde{Re}_l \quad \forall l \in L \quad (3.2)$$

$$\sum_{j=1}^J \tilde{z}_{ij} = (1 - \tilde{\gamma}) \cdot \sum_{l=1}^L \tilde{x}_{li} \quad \forall i \in I \quad (3.3)$$

$$\sum_{k=1}^K \tilde{w}_{ik} = \tilde{\gamma} \cdot \sum_{l=1}^L \tilde{x}_{li} \quad \forall i \in I \quad (3.4)$$

$$\sum_{m=1}^M \tilde{v}_{jm} = \sum_{i=1}^I \tilde{z}_{ij} \cdot \widetilde{we} \cdot \widetilde{cont} \cdot \tilde{\alpha}_j \quad \forall j \in J \quad (3.5)$$

$$\sum_{l=1}^L \tilde{x}_{li} \leq \widetilde{Cap1}_i \cdot y1_i \quad \forall i \in I \quad (3.6)$$

$$\sum_{i=1}^I \tilde{z}_{ij} \leq \widetilde{Cap2}_j \cdot y2_j \quad \forall j \in J \quad (3.7)$$

$$\sum_{i=1}^I \tilde{w}_{ik} \leq \widetilde{Cap3}_k \quad \forall k \in K \quad (3.8)$$

$$\sum_{j=1}^J \tilde{v}_{jm} \leq \widetilde{Cap4}_m \quad \forall m \in M \quad (3.9)$$

$$\sum_{m=1}^M \tilde{v}_{jm} \leq M \cdot y2_j \quad \forall j \in J \quad (3.10)$$

$$y1_i, y2_j \in (0,1) \quad \forall i \in I, \quad \forall j \in J \quad (3.11)$$

$$\tilde{x}_{li}, \tilde{z}_{ij}, \tilde{w}_{ik}, \tilde{v}_{jm} \text{ are non - negative fuzzy numbers} \quad (3.12)$$

According to the constraint (3.2), all of the end-of-life products must be collected by the collection centers from the customer zones. In other words, collection requests of the customers should be fully satisfied. Constraint (3.3) presents the conservation of flow constraint for the recycling facilities. Thus, one can calculate the quantity of recyclable products by using this constraint. Similarly, the remaining fraction of the total collected products should be disposed of as in the constraint (3.4). This constraint also presents a balance equation for the disposal sites. One can calculate the amounts of recycled materials (in kilograms) transported from the recycling facilities to the manufacturing plants by using the constraint (3.5). In this constraint, in order to obtain the total amounts of the recycled materials in each recycling facility, the quantity of recyclable products should be multiplied by the weight of the products, rate of the

contribution of material and the recycling fraction whose values are also defined as fuzzy numbers. Constraint sets (3.6), (3.7), (3.8) and (3.9) are capacity limitations for the collection/inspection centers, recycling facilities, disposal sites and manufacturing plants, respectively. Constraint (3.10) ensures that transportation of the recycled materials cannot be performed from an unopened recycling facility. Constraint (3.11) represents the binary variables for opening of the collection/inspection centers and recycling facilities. Finally, constraint (3.12) enforces the non-negativity restrictions for the decision variables represented by triangular fuzzy numbers.

3.4 Solution of Deterministic Problem via Seeker Optimization Algorithm (SOA)

For a RL network design problem, when the size of problem grows, it acts like a combinatorial optimization problem whose computational time to yield an optimal solution grows exponentially (Sim et al., 2004). Actually, NP-hardness of the logistics network design problems is discussed in many researches (Davis & Ray, 1969; Jayaraman and Ross, 2003; Gen et al., 2006; Pishvae et al., 2010). For instance, it is emphasized by Pishvae et al. (2010a) that RL network design models contain two separate problems namely capacitated facility location problem and flow optimization. Since the capacitated facility location problem is NP-complete (Davis & Ray, 1969), the RL network design problem which is discussed in this chapter is also NP-hard. In addition, Gen et al. (2006) highlighted that when each facility has limited capacity and there is an upper bound on number of facilities to be opened, the problem is referred as the capacitated p -median facility location problem and it is also NP-hard problem (Garey & Johnson, 1979). Since RL network design problems involve capacitated p -median facility location problem, it is also NP-hard. For this reason, solving this kind of problems in a large scale by exact algorithms may take long computational time. For this reason, many meta-heuristic algorithms such as genetic algorithm (GA) (Gen et al., 2006; Altiparmak et al., 2006; Altiparmak et al., 2009; Wang & Hsu, 2010; Costa et al., 2010; Hosseinzadeh & Roghanian, 2012), simulated annealing (SA) (Pishvae et al., 2010b; Subramanian et al., 2013), memetic algorithm (Pishvae et al., 2010a), ant colony optimization (ACO) (Wang, 2009; Martinez & Zhang, 2011), collaborative agent team (CAT) (Carle et al., 2012) have been developed to solve supply chain, RL and CLSC network design problems. However, to the best of our knowledge, SOA has

recently not been applied to any discrete combinatorial optimization problem based on the review of available literature. With this motivation, this section presents a priority-based SOA for solving a generic deterministic RL network design problem. In other words, SOA is integrated with priority-based encoding method and a decoding procedure. The fundamental articles which present the application of SOA can be summarized as follows: A novel SOA depends on the concept of simulating the act of human's intelligent search with their memory, experience and uncertainty reasoning was proposed by Dai et al. (2007) for real parameter optimization. According to Dai et al. (2007) and Dai et al. (2010a), when SOA is compared to continuous GA, DE and PSO for solving global numerical optimization problems, it is more robust, faster and efficient in converging to near global optimum solutions. SOA based method is also applied by Dai et al. (2010b) to design IIR filters. Economic load dispatch problems in test power systems was solved by Shaw et al. (2011) using SOA. A stochastic search technique depending on SOA was proposed by Guney and Basbug (2011) for null steering of linear antenna arrays. Optimization shape parameters of a polysilicon variable-capacitance micro-motor were determined via SOA (Ketabi & Navardi, 2012). In addition, SOA is applied for optimizing different tunable parameters of an autonomous power system (Banerjee et al., 2012). In order to provide optimal reactive power dispatch by considering static voltage stability and voltage deviation, SOA was used by Dai et al. (2009). To the best of our knowledge, swarm intelligent approaches such as PSO and SOA have not been utilized so far in the literature for solving any supply chain, RL and CLSC network design problems which are discrete and combinatorial optimization problems. Thus, the main purpose of this section is to modify available decoding procedure for realization of these algorithms on a basic deterministic RL network design problem. While realizing the SOA and PSO algorithms, unbalanced transportation problems are decoded without adding any dummy nodes apart from the available literature. This improvement yields more efficient encoding/decoding procedures and also computational efficiency. Furthermore, equal transportation cost characteristic is also taken into account for better reflection of the real-life applications. In summary, a priority based-SOA procedure for a crisp RL network design problem is proposed and results of different swarm intelligent approaches are reported in this section.

3.4.1 Details of Proposed SOA Based Solution Methodology

SOA is a novel swarm intelligence stochastic search technique depends on humans' intelligent search behaviors using their memory, experience, uncertainty reasoning and active collaboration (Dai et al., 2007). Actually, it is a multi-population based meta-heuristic search algorithm which focuses on human searching behavior in finding solution of many optimization tasks encountered in many areas of human life (Dai et al., 2010a; Dai et al., 2010b). In this meta-heuristic, the search direction is calculated based on empirical gradient by assessing the response against position changes. Besides, step length is computed depending upon uncertainty reasoning mechanism by utilizing a basic fuzzy rule (Shaw et al., 2011). Briefly, human understanding and searching capability can be seen as the main characteristics of this algorithm. For analogy of this algorithm, investigating the black boxes by a search group can be given as an example for human searching behavior. Additionally, most important features of SOA were emphasized by Guney and Basbug (2011) as follows:

- Similar to other evolutionary algorithms, SOA has population which consists of seekers. In other words, each individual of the population represents a seeker. The overall population is divided into m -subpopulations randomly so as to guarantee social characteristics for information sharing. These subpopulations search for optimal solution over different domains of the solution space.
- In order to calculate the search direction, proportional selection rule is carried out. In fact, this can improve diversification property and global search ability.
- The step length is computed by utilizing a fuzzy reasoning procedure. Actually, using linguistics variables and simple if-else control rules may be the best way to characterize the uncertain reasoning of human searching behavior.
- SOA also takes into account the cooperation between the seekers while realizing the group dynamics.

3.4.2 Solution Representation (Encoding)

Before implementation phase of the algorithm, representation of the solution is required for a RL network design problem. It should be noted here that the choice of

the representation may affect the performance of applied meta-heuristic algorithm (Gen et al., 2006). Tree based representation may be the best alternative for representing network problems. These encoding methods are summarized as follows:

- I. *Matrix encoding method* (Dimension of matrix is $K \times J$, where K and J represents numbers of sources and depots). This encoding procedure is very ordinary but needs to use special crossover and mutation operators and also huge memory (Michalewicz et al., 1991).
- II. *Spanning tree method* (Length of array $K+J-2$). Actually, this method utilizes a private algorithm based on the Prüfer number. However, infeasible solutions may be produced through this representation. In order to prevent this drawback, additional repair mechanisms may be required (Gen & Cheng, 1997).
- III. *Priority-based encoding method* (Chromosome's length to $K+J$). This technique does not need to use any repair mechanism (Gen et al., 2006; Gen & Cheng, 1997; Gen & Cheng, 2000).

In this section, priority based encoding procedure is utilized and the chromosome is divided into four segments as denoted in Figure 3.2.

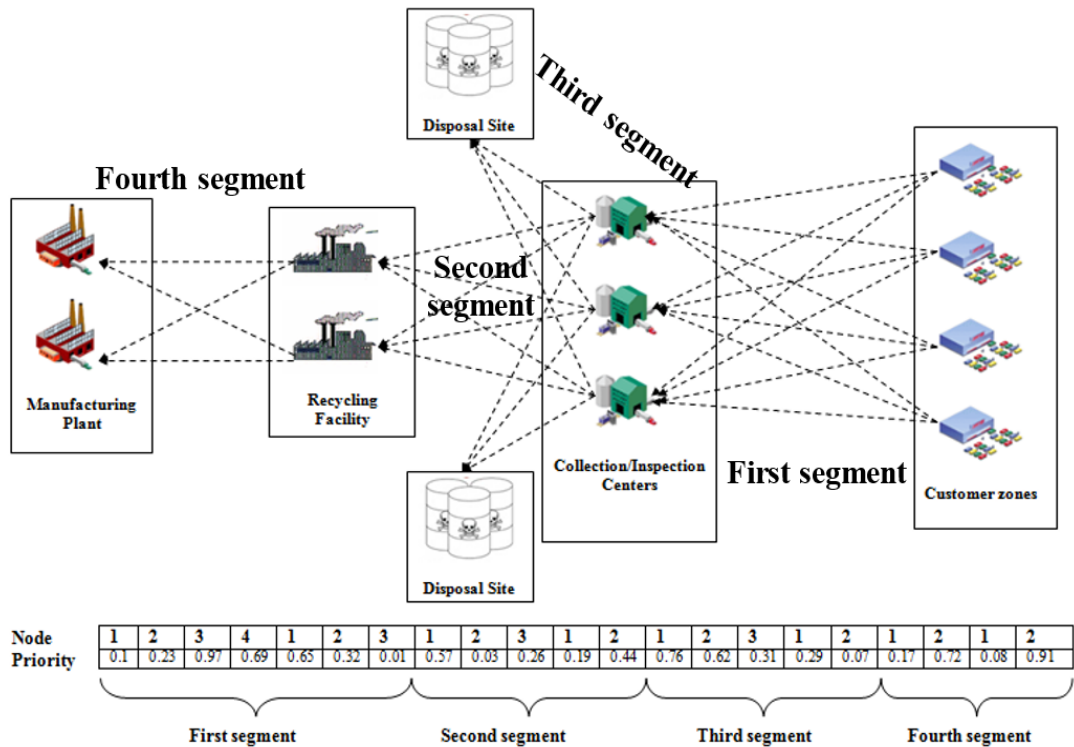


Figure 3.2 An illustration of RL network with its segments and encoding

Unfortunately, continuous nature of SOA prohibits the application of this algorithm to discrete combinatorial optimization problems. In order to accomplish this shortcoming, largest-value-order (LOV) based on random key representation is utilized in order to convert the solution vector with continuous positions to discrete node (source/depots) permutation (Taşgetiren et al., 2007; Li & Yin, 2013). Actually, random key method encodes a solution by using random numbers. These numbers are utilized as sort keys for decoding the solution. The main difference between this encoding and others in the literature is the usage of random numbers as tags to represent solutions (Bean, 1994). For better understanding of the overall encoded solution, a transportation tree including three collection centers and four customer zones is depicted in Figure 3.3. The regarding cost matrix (unit transportation costs between these collection centers and customer zones) and a priority-based encoding are also given in the same figure.

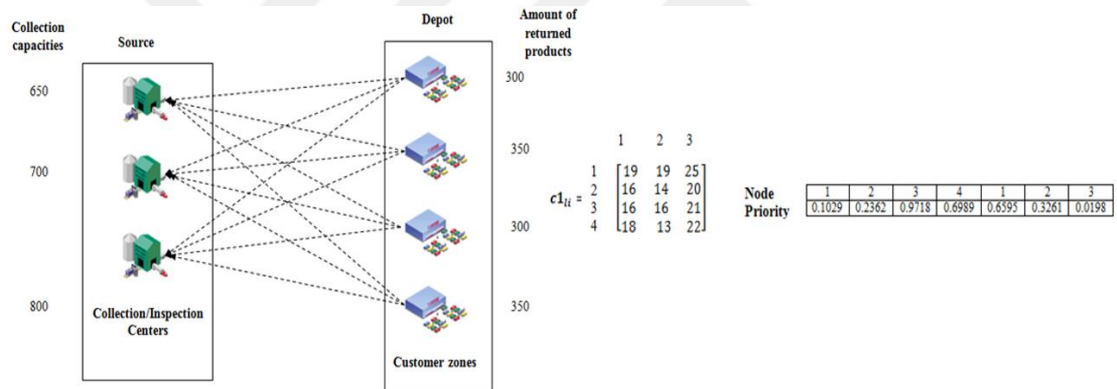


Figure 3.3 Transportation tree related to the first segment

3.4.3 Proposed Decoding Procedure

The entire decoding procedure for the multi-echelon RL network design problem is shown in Table 3.3. Decoding of the second, third and fourth segments of the solution vector can be performed after decoding of the first segment. Because, the number of collection center and amount of returned products shipped to each collection center should be known for decoding the next stages (Pishvaei et al., 2010b). The revised version of decoding algorithm for the priority-based encoding which was developed by Gen and Cheng (2000) is given in Table 3.5.

Table 3.3 Multi-stage decoding algorithm for the encoded solution

<i>Step 1:</i>	$y1_i = 0, y2_j = 0, x_{li} = 0, z_{ij} = 0, w_{ik} = 0,$ $v_{jm} = 0$ for $\forall l, \forall i, \forall j, \forall k$ and $\forall m$
<i>Step 2:</i>	Calculate $x_{li} \forall l, \forall i$ by using the revised version of Gen and Cheng's (2000) decoding algorithm in Table 3.5 (1 st stage decoding).
<i>Step 3:</i>	For $i=1$ to $i=I$ If $\sum_i x_{li} > 0$ then $y1_i = 1$
<i>Step 4:</i>	Calculate $z_{ij} \forall i, \forall j$ by using the revised decoding algorithm (2 nd stage decoding).
<i>Step 5:</i>	For $j=1$ to $j=J$ If $\sum_i z_{ij} > 1$ then $y2_j = 1$
<i>Step 6:</i>	Calculate $w_{ik} \forall i, \forall k$ by using the revised decoding algorithm (3 rd stage decoding).
<i>Step 7:</i>	Calculate $v_{jm} \forall j, \forall m$ by using the revised decoding algorithm (4 th stage decoding).

Different from the existing literature (Gen et al., 2006; Altıparmak et al., 2006; Altıparmak et al., 2011; Pishvae et al., 2010b), we coded the decoding algorithm for balancing the problem without introducing any dummy depot (customer zone) on each segment of the chromosome. In addition, our decoding procedure takes into account the equal transportation cost values.

The decoding procedure is reiterated for the first segment until all the used products at the customer zones are collected by the collection centers. In contrast to the available decoding algorithms, we assigned very big negative value (-99999) to leaving nodes (collection centers with empty capacity or customer zones with no returned products) since the continuous nature of SOA.

The trace table of the sample chromosome given in Figure 3.3 (only 1st segment of the solution vector) can be displayed as in the following Table 3.4.

Table 3.4 Trace table for encoding procedure (1st Segment)

Iter.	$v(l+i)$ vector	$Cap1_i$	Rel_i	l	i	x_{li}
0	(0.1029 0.2362 0.9718 0.6989 0.6595 0.3261 0.0198)	(650 700 800)	(300 350 300 350)	3	(1, 2)	300
1	(0.1029 0.2362 -99999 0.6989 0.6595 0.3261 0.0198)	(350 700 800)	(300 350 0 350)	4	2	350
2	(0.1029 0.2362 -99999 -99999 0.6595 0.3261 0.0198)	(350 350 800)	(300 350 0 0)	(2*, 3)	1	350
3	(0.1029 -99999 -99999 -99999 -99999 0.3261 0.0198)	(0 350 800)	(300 0 0 0)	(4, 2, 3, 1*)	2	300
4	(-99999 -99999 -99999 -99999 -99999 0.3261 0.0198)	(0 50 800)	(0 0 0 0)	-	2	-
5	(-99999 -99999 -99999 -99999 -99999 -99999 0.0198)	(0 50 800)	(0 0 0 0)	-	3	-
6	(-99999 -99999 -99999 -99999 -99999 -99999 -99999)	-	-	-	-	-

Table 3.5 Pseudo code of revised decoding algorithm for priority-based encoding (1st Segment)

Procedure: Decoding of the chromosome for the first segment (1st Stage Decoding)

Inputs: I : set of collection centers, L : set of Customer zones, Re_l : amount of returned products from customer zone l , $Capl_i$: collection capacity of collection center i

$c1_{li}$: unit transportation cost of returned product from customer zone l to collection center i

$v(l+i)$: encoded solution (chromosome)

Outputs: x_{li} : quantity of returned product shipped to collection center i from customer zone l

If $\sum_i Capl_i \geq \sum_l Re_l$ (Unbalanced transportation problem)

Step 1: $x_{li} = 0 \quad \forall i, \forall l$ While $v(l+i) \neq -99999$ (any huge negative number)

Step 2: Select a node based on $\pi = \arg \max \{v(t), t \in |L| + |I|\} \quad \forall i \in I, \forall l \in L$

Step 3: If $\pi \in L$ then a customer zone is selected $l^* = \pi$

$i^* = \arg \min \{c1_{li} \mid v(i) \neq -99999 \mid i \in I\}$ Select a collection center with the lowest transportation cost and no empty capacity

If length of $i^* > 1$ (two collection centers with equal transportation cost), then select one of them randomly

Else $\pi \in I$ then a collection center is selected $i^* = \pi$

$l^* = \arg \min \{c1_{li} \mid v(l) \neq -99999 \mid l \in L\}$ Select a customer zone with the lowest transportation cost and no empty returned products

If length of $l^* > 1$ (two customer zones with equal transportation cost), then select one of them randomly

Step 4: $x1_{l^*i^*} = \min(Re_{l^*}, Cap1_{i^*})$ (Assign available amount of returned products)

$Re_{l^*} = Re_{l^*} - x1_{l^*i^*}$ and $Cap1_{i^*} = Cap1_{i^*} - x1_{l^*i^*}$ Update the capacities and amount of returned products on l^* and i^*

Step 5: If $Cap1_{i^*} = 0$ then $v(i^*) = -99999$, If $Re_{l^*} = 0$ then $v(l^*) = -99999$

Step 6: Calculate the $\emptyset = \sum_i \sum_l x1_{li}$ if $\emptyset = \sum_l Re_l$ and $Cap1_{i^*} > 0$ then $v(i^*) = -99999$ and

find $\{i^{**} \in I \mid Cap1_{i^{**}} > 0\}$ and then $v(i^{**}) = -99999$ else go to step 2.

Step 7: If $v(l+i) = -99999 \quad \forall i, \forall l$ then calculate the fitness = $\sum_i \sum_l c1_{li} \cdot x1_{li}$ total transportation cost

between the first stage facilities, Else go to step 1.

Step 8: If $\sum_i Capl_i = \sum_l Re_l$ (Balanced transportation problem) Then perform Step 5 and then terminate the algorithm at the end of step 7 (Ignore Step 6).

3.4.4 Implementation Steps of SOA

As mentioned previously, SOA is a multi-population based meta-heuristic algorithm for generally solving continuous numerical optimization problems. In the first step of this algorithm, the swarm as a search population is divided into m (in generally three) sub-populations randomly. Actually, all the seekers in the same sub-population comprise a neighborhood. According to this algorithm, a search direction, $sd_{ij}(k)$ and a step length $sl_{ij}(k)$ are computed separately for each seeker i on each dimension j at each iteration k . Here, $\overrightarrow{sl_{ij}}(k) \geq 0$ and $\overrightarrow{sd_{ij}}(k) \in \{-1, 0, +1\}$ are vectors where -1 and $+1$ represent negative and positive directions while 0 means current position on dimension j (Dai et al., 2007; Dai et al., 2010a). The current position of each seeker i for each iteration k can be shown as $\overrightarrow{x_{ij}}(k) = [x_{i1}, x_{i2}, x_{i3}, \dots, x_{ij}]$, where j corresponds to the j^{th} dimension or variable. For instance, when the examined RL network design problem consists of four customer zones, three collection centers, two recycling facilities, two disposal sites and two manufacturing plants, there will be totally 21 nodes on the solution vector for each seeker. In other words, dimension size (j) will be equal to 21.

3.4.4.1 Calculation of the search direction

The search direction is determined depending on empirical gradient by considering responses against position changes (Shaw et al., 2011). In fact, search direction is calculated based on a compromise among egotistic, altruistic and pro-activeness behaviors according to the seeker's rational experience. Hence, mathematical formulation of the search direction for the i^{th} seeker can be given as the stochastic combination of all these above directions as follows (Dai et al., 2010a; 2010b):

$$sd_{ij}(k) = \text{sign}(\omega \cdot sd_{ij,pro} + \Phi 1 \cdot sd_{ij,ego} + \Phi 1 \cdot sd_{ij,alt}) \quad (3.13)$$

where $\text{sign}(\cdot)$ represents signum function on each dimension j of the solution vector and ω denotes inertia weight. This parameter is utilized for steadily decreasing the effect of local search comes from pro-activeness behavior. It also may provide a balance between exploration and exploitation. In general, it is linearly decreased from 0.9 to 0.1 along a run. Moreover, $\Phi 1$ and $\Phi 2$ are uniformly distributed random numbers in the interval $[0, 1]$.

The flowchart of SOA utilized in this section can be visualized as in Figure 3.4.

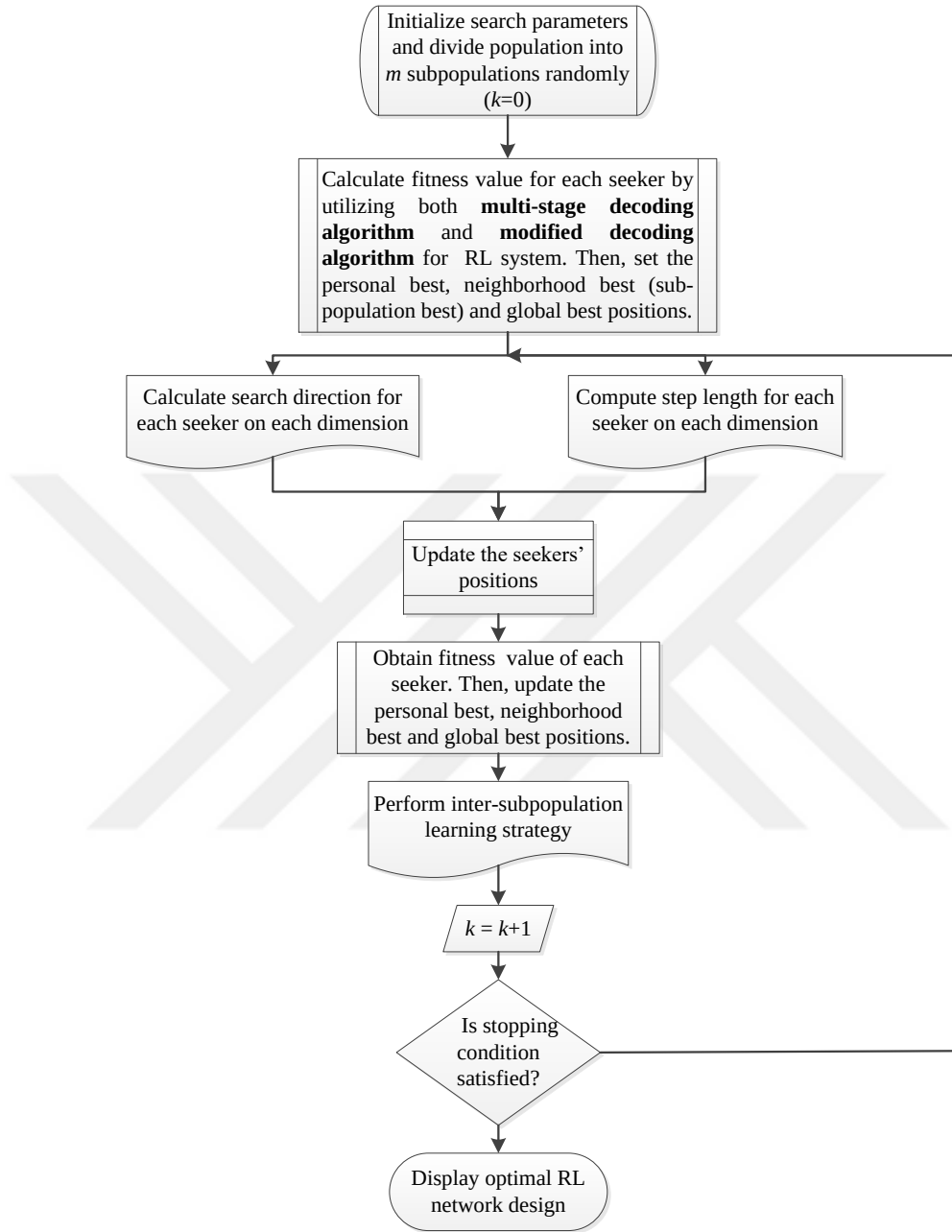


Figure 3.4 Flowchart of SOA adapted from (Shaw et al., 2011; Guney & Basbug, 2011)

According to egoistic behavior which is one of the extreme types of co-operative behavior, each seeker as a sophisticated agent is uniformly egoistic. This means that they should move according to his/her personal best position $p_{ij,best}$ (Dai et al., 2010a). In fact, this behavior represents cognitive learning and corresponds to cognitive part of the velocity vector in PSO. So, egoistic direction can be formulated as follows:

$$sd_{ij,ego}(k) = p_{ij,best}(k) - x_{ij}(k) \quad (3.14)$$

According to altruistic behavior, seekers contact to each other to arrange their behaviors in response to others to succeed the targets. Thus, seekers display entirely pro-group behavior which means social learning and simultaneously go towards neighborhood best position g_{best} (Guney & Basbug, 2011). This behavior corresponds to social part of the velocity vector in PSO.

$$sd_{ij,alt}(k) = g_{best}(k) - x_{ij}(k) \quad (3.15)$$

Finally, seekers may have pro-activeness property or they may be pro-active to adjust their search direction and show goal-directed behavior according to the response to their past positions. In other words, the positions in the next iterations can be influenced by the past behaviors (Shaw et al., 2011).

$$sd_{ij,pro}(k) = x_{ij}(k1) - x_{ij}(k2) \quad (3.16)$$

It is assumed that the position at iteration $k1$, $(x_{ij}(k1))$ is better than the position at iteration $k2$, $(x_{ij}(k2))$. Actually, there are the best and worst positions resulted from the k , $k-1$ and $k-2$ iterations.

3.4.4.2 Computing the Step Length

According to the main principle on human searching behavior, one can provide near-optimal solutions in a narrower neighborhood of the point with lower fitness value; conversely, in a wider neighborhood of the point with higher fitness function value. In this context, fuzzy reasoning mechanism may be the most appropriate way to represent the linguistic assessments comes from human's behavioral pattern at the time of searching (Shaw et al., 2011). In fact, fuzzy systems take root from the requirement of describing complex systems by using linguistic terms. So, the uncertain reasoning of human searching behavior may be the best described by these natural linguistic descriptions and a simple fuzzy rule. For instance, the following example can be given for a linguistic description while calculating the step length; “*If fitness value is small, then step length is short*”. Thus, we can utilize fuzzy systems in order to understand and describe linguistic terms while simulating the human searching

behavior (Guney & Basbug, 2011). In the conditional part of the linguistic description, the fitness values of all the seekers are sorted in descending order (for minimization problems); otherwise in ascending order (for maximization problems) and convert into the sequence numbers from 1 to S as the inputs of uncertain reasoning mechanism (condition part of the fuzzy reasoning for each seeker). Because of the universe of discourse consists of a set of discrete numbers $(1, 2, \dots, S)$, the following linear membership function is used in the conditional part of the fuzzy rule.

$$\mu_i = \mu_{max} - \frac{S - I_i}{S - 1} \cdot (\mu_{max} - \mu_{min}) \quad (3.17)$$

where I_i represents the order number of $x_{ij}(k)$ after sorting the fitness values and μ_{max} is the maximum membership degree value which is equal to or less than 1.0. In this section, value of this parameter, μ_{max} is stated as 0.95. In the action part of the aforementioned fuzzy reasoning mechanism, the Bell membership function which is shown in below Figure 3.5 is utilized in the literature so far. Also, the mathematical formulation of this membership function can be given as follows:

$$\mu(x) = e^{-x^2/2\delta^2} \quad (3.18)$$

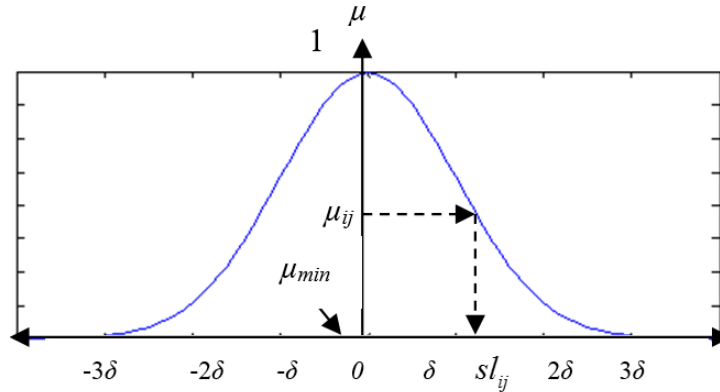


Figure 3.5 Bell membership function for action part of fuzzy reasoning mechanism

Moreover, parameter, i.e., δ , of the Bell membership function can be determined as follows:

$$\vec{\delta}_{ij} = \omega \times abs(\vec{X}_{best} - \vec{X}_{rand}) \quad (3.19)$$

The membership degree values of the inputs beyond $[-3\delta, +3\delta]$ are less than 0.0111 ($\mu(\pm 3\delta) = 0.0111$) and the inputs whose membership degree beyond $[-3\delta, +3\delta]$ in the universe of discourse can be ignored. Thus, the minimum membership degree $\mu_{min} = 0.0111$ is set. The used parameter in (3.19), ω aims at reducing the step length with increasing iterations so as to gradually improve the search precision. Additionally, $\vec{X}_{best}$ and $\vec{X}_{rand}$ correspond to the best seeker and a randomly chosen seeker respectively from the same sub-population. It should be emphasized here that $\vec{X}_{rand}$ is different from $\vec{X}_{best}$ and δ is commonly used by all the seekers in the same sub-population. In order to convert μ_i into a vector μ_{ij} , the following Equation (3.20) is introduced. This also provides randomness on each dimension and improves local search property:

$$\mu_{ij} = Rand(\mu_i, 1) \quad j = 1, 2, \dots, 21 \quad (3.20)$$

$$sl_{ij} = \delta_{ij} \sqrt{-\ln(\mu_{ij})} \quad (3.21)$$

Finally, step length is calculated for each dimension of each seeker by utilizing the action part of the fuzzy reasoning as given above Equation (3.21).

3.4.4.3 Updating the Positions of Seekers

After computing the search direction and step length, the positions for each seeker i will be updated on each dimension j as follows:

$$x_{ij}(k+1) = x_{ij}(k) + sl_{ij}(k) \times sd_{ij}(k) \quad (3.22)$$

where $x_{ij}(k+1)$ is the position of j^{th} dimension of i^{th} seeker at iteration $k+1$; $sl_{ij}(k)$ represents the step length of j^{th} dimension of i^{th} seeker at iteration k and $sd_{ij}(k)$ is the search direction of j^{th} dimension of i^{th} seeker at iteration k .

3.4.4.4 Inter-subpopulation Learning Strategy

According to inter-subpopulation learning strategy, all of the subpopulations should learn from each other about the optimal information so far. In other words, good solutions yielded by each subpopulation should be shared among these subpopulations

for increasing the diversification in the overall population. For this reason, the positions of two worst seekers of each subpopulation are combined with the best one in each of the other subpopulations by utilizing the following binomial crossover operator (Shaw et al., 2011):

$$x_{m_n,j,worst} = \begin{cases} x_{m^*,j,best} & \text{If } rand_j \leq 0.5 \\ x_{m_n,j,worst} & \text{Otherwise} \end{cases} \quad (3.23)$$

where $x_{m_n,j,worst}$ is the j^{th} dimension of the n^{th} worst seeker in the m^{th} subpopulation and $x_{m^*,j,best}$ represents j^{th} dimension of the seeker with best position in the m^{*th} subpopulation ($m \neq m^*$).

3.4.5 Results of Deterministic Problem via PSO and SOA

The application of the proposed priority-based SOA is illustrated through a basic example for depicting the validity and practicality. There are four customer zones, three potential collection centers, two potential recycling facilities, two fixed disposal sites and two manufacturing plants in the example. The following crisp data is used for presenting the RL network design problem. Amounts of returned products from different customer zones are 300, 350, 300 and 350 units, respectively. The weights of the products are the same and equal to 10 kilogram. Disposal fraction is determined as 10%. Recyclable material contribution for the returned products is 70% percent of product weight. The unit transportation costs between the recycling facilities and manufacturing plants are \$55, \$50, \$60 and \$45, respectively. Other transportation costs (collection centers-recycling facilities, collection centers-disposal sites) are given by the following Table 3.6.

Table 3.6 Other transportation costs between the different stages of RL network

Collection center	Recycling Facility-1	Recycling Facility-2	Disposal Site-1	Disposal Site-2
1	\$10	\$15	\$17	\$15
2	\$18	\$25	\$18	\$13
3	\$30	\$32	\$20	\$25

Capacities of the collection centers are 650, 700 and 800 units, respectively. Moreover, fixed opening costs for the collection centers are specified as \$100000, \$150000 and \$200000, respectively. After recycling process, the recycled materials are shipped to the manufacturing plants. The capacities of the manufacturing plants for these materials (in kg) are 3500 and 2852, respectively. Finally, the capacities of disposal sites are 100 and 50 units, respectively.

In order to evaluate the proposed decoding algorithm which is given in Table 3.5, three different RL systems are generated in addition to the given data above. In detail, all of the transportation problems in RL network design problem are unbalanced. However, some transportation stages may be balanced or may have unnecessary facilities with additional capacity. These problems are portrayed in Figures 3.6 to 3.8. Parameters of the proposed SOA algorithm are given in Table 3.7. Computational results for different test problems for SOA and PSO are reported in Table 3.8.

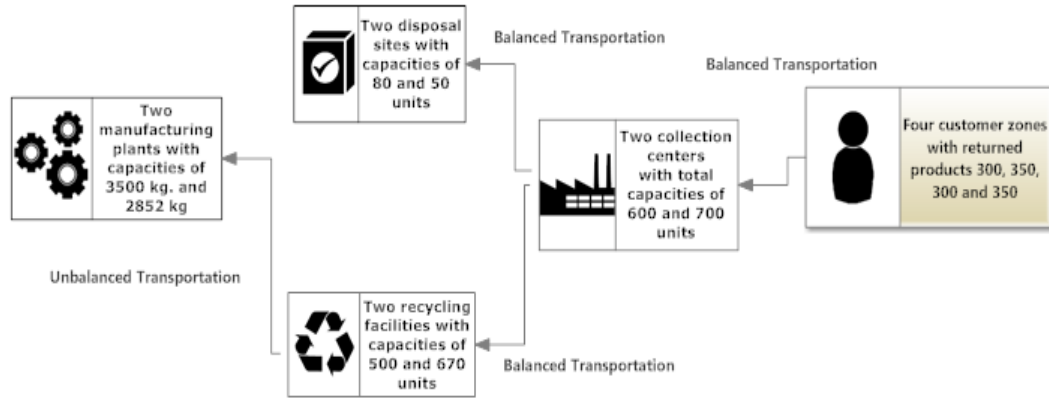


Figure 3.6 A RL network system with hybrid balanced/unbalanced transportation problems (Type-1)

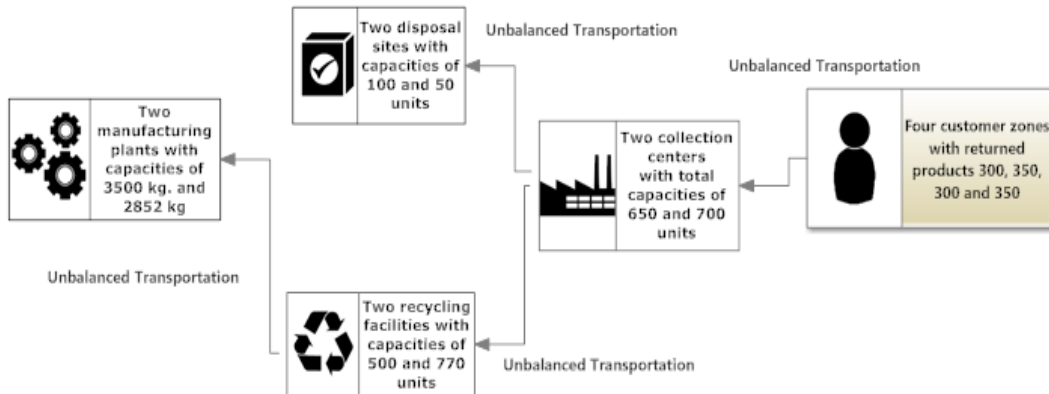


Figure 3.7 A RL network system with fully unbalanced transportation problems (Type-2)

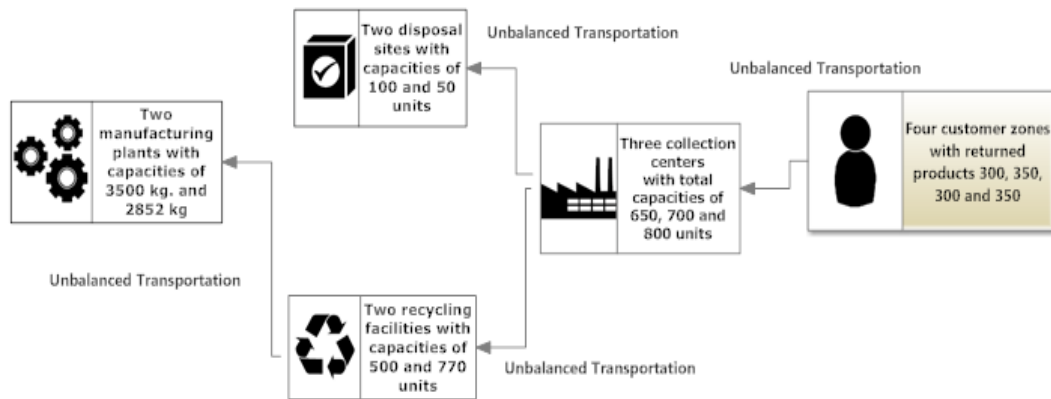


Figure 3.8 A RL network with fully unbalanced transportation problems and extra unnecessary collection center (Type-3)

Table 3.7 Parameters related to SOA

Global population size	150
Size of subpopulation 1	50
Size of subpopulation 2	50
Size of subpopulation 3	50
Inertia weight	0.9
Generation number	50
Independent run size	20

Table 3.8 Computational results of SOA and PSO algorithms

Test Problem	Total seeker population size	Generation Number	# of optimum solutions by SOA	SOA objective value			CPU time(seconds)			LINGO 9.0 Objective Value	LINGO time (seconds)
				Max	Min	Ave	Max	Min	Ave		
Type-1	30	5	20	1290170	1290170	1290170	0,47	0,21	0,22	1290170	0-1
Type-2	100	10	16	1290170	1289815	1289863	1,20	1,14	1,15	1289815	0-1
Type - 3	150	50	9	1402830	1289815	1298684,25	9,59	9,18	9,34	1289815	0-1
Test Problem	Total particle population size	Generation Number	# of optimum solutions by PSO	PSO objective value			CPU time (seconds)			LINGO 9.0 Objective Value	LINGO time (seconds)
				Max	Min	Ave	Max	Min	Ave		
Type-1	30	5	20	1290170	1290170	1290170	0,47	0,21	0,22	1290170	0-1
Type-2	100	10	17	1289965	1289815	1289828	1.43	1.39	1.41	1289815	0-1
Type - 3	150	50	None	1489815	1289965	1323810	12.98	10.71	11.45	1289815	0-1

Furthermore, optimal RL configuration and optimal amounts of reverse flows between the different stages can be seen for type-3 RL system from the following Figure 3.9. Finally, obtained results are compared with PSO algorithm which is another swarm intelligence technique. Summary of the results show that SOA outperforms than PSO for more complex RL network design problem (type-3) in terms of both solution quality and computational time. For instance, PSO could not find optimal solution within 20 runs for this type of problem. On the other hand, SOA found optimal solution for 9 of 20 runs.

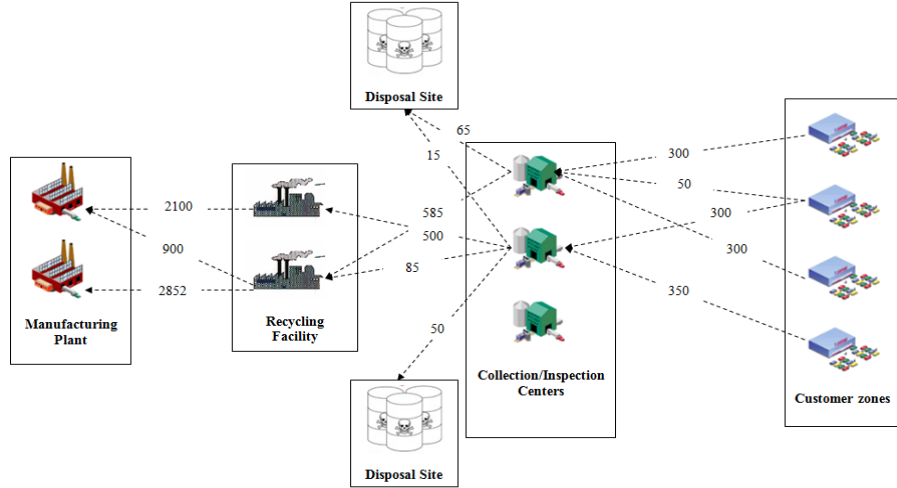


Figure 3.9 Optimal RL network configuration and reverse flow quantities under crisp environment

3.5 Different Solution Methodologies for the FFRLND Problem

In this sub-section, several indirect solution approaches from the literature for solving FFLP problems are introduced. Additionally, basics of the proposed parametric solution method are also presented. Thereafter, in Section 3.6, fuzzy efficient solutions of the stated FFRLND problem are provided by using these methods in a more confidential way. A FFLP problem with m fuzzy equality/inequality constraints and n fuzzy variables can be formulated as follows:

$$\text{Min or Max } \tilde{z} \approx \sum_{j=1}^n \tilde{c}_j \cdot \tilde{x}_j \quad (3.24)$$

$$\text{Subject to: } \sum_{j=1}^n \tilde{a}_{ij} \cdot \tilde{x}_j \{ \lesssim, \approx, \gtrsim \} \tilde{b}_i \quad \forall i \in I \quad (3.25)$$

$$\tilde{x}_j \text{ is a non - negative triangular fuzzy number, } \forall j \in J \quad (3.26)$$

3.5.1 Allahviranloo et al.'s (2008) Approximation Method

Allahviranloo et al. (2008) proposed a method for solving the FFLP problems based on comparison of the fuzzy numbers. In fact, the basis of this method depends on the approximation of the triangular fuzzy numbers which are sited at the objective function and the constraints to the core of the nearest symmetric triangular fuzzy number. For this purpose, they utilized a kind of defuzzification technique and introduced a linear ranking function similar to the ranking function of Bortolan and Degani (1985). In this method, a triangular fuzzy number is defined as in the following form:

Definition 3.5.1. A fuzzy set $\tilde{A}$ is called a triangular fuzzy number with peak (or center) A , left width A' and right width A'' if its membership function has the following form:

$$\mu_{\tilde{A}}(x) = \begin{cases} 1 - \frac{A-x}{A'} & A - A' \leq x \leq A \\ 1 - \frac{x-A}{A''} & A \leq x \leq A + A'' \\ 0 & \text{Otherwise} \end{cases} \quad (3.27)$$

The parametric form of this triangular fuzzy number can be written as follows:

$$\tilde{A} = (A'.(1-r) + A, A''.(1-r) + A) \quad (3.28)$$

The ranking function utilized in this method can be expressed for any arbitrary fuzzy number with r -cut representation $\tilde{A} = (\underline{A(r)}, \overline{A(r)})$ as follows:

$$\Re(\tilde{A}) = 1/2. \int_0^1 (\underline{A(r)}) + \int_0^1 \overline{A(r)} \quad (3.29)$$

For a triangular fuzzy number, this reduces to:

$$\Re(\tilde{A}) = A + 1/4. (A'' - A') \quad (3.30)$$

According to this ranking function, two triangular fuzzy numbers, $\tilde{A}$ and $\tilde{B}$ can be compared as follows: $\tilde{A} \succeq \tilde{B}$ if and only if $A + 1/4. (A'' - A') \geq B + 1/4. (B'' - B')$. They also used the same multiplication and special type of distance function as represented in the study of Bellman and Zadeh (1970). Thereafter, the FFLP problem whose compact form is given in Section 3.5 can be transformed into the crisp equivalent form through the method of Allahviranloo et al. (2008) as follows:

$$\text{Min or Max } \tilde{z} \cong \sum_{j=1}^n \left(c_j - \frac{1}{4} \cdot c'_j + \frac{1}{4} \cdot c''_j \right) \cdot x_j - \sum_{j=1}^n \frac{c_j}{4} \cdot x'_j + \sum_{j=1}^n \frac{c_j}{4} \cdot x''_j \quad (3.31)$$

$$\sum_{j=1}^n \left(a_{ij} - \frac{1}{4} \cdot a'_{ij} + \frac{1}{4} \cdot a''_{ij} \right) \cdot x_j - \sum_{j=1}^n \frac{a_{ij}}{4} \cdot x'_j + \sum_{j=1}^n \frac{a_{ij}}{4} \cdot x''_j \{ \leq, =, \geq \} b_i - \frac{1}{4} \cdot b'_i + \frac{1}{4} \cdot b''_i \quad \forall i \quad (3.32)$$

$$x_j - \frac{1}{4} \cdot x'_j + \frac{1}{4} \cdot x''_j \geq 0 \quad \forall j \in n \quad (3.33)$$

$$x_j \geq x'_j \quad \forall j \in n \quad (3.34)$$

where $\tilde{C} = (c_j, c'_j, c''_j) \ j = 1, 2, \dots, n$ are the objective function coefficients, $\tilde{A} = (a_{ij}, a'_{ij}, a''_{ij}) \ i = 1, 2, \dots, m$ present the coefficient matrix of the constraints, $\tilde{B} = (b_i, b'_i, b''_i)$ are the right hand side values of the constraints and finally $\tilde{X} = (x_j, x'_j, x''_j)$ are the fuzzy decision variables. Before applying this method to the stated FFRLND problem, an index $t=1, 2$, and 3 is added to all uncertain parameters and decision variables in order to represent the core, left and right margins of a triangular fuzzy number, respectively. Moreover, while performing this transformation method, it is required to introduce new state variables, i.e., $Stv1_t$ and $Stv2_{jt}$ for the fuzzy multiplication operation of three triangular fuzzy parameters used in constraint (3.5) into the Section 3.3.3. The fuzzy multiplication operation is presented as follows:

Theorem 3.5.1. If $\tilde{A}$ and $\tilde{B}$ are two positive fuzzy numbers of LR -type: $\tilde{A} = (A, A', A'')_{LR}$ and $\tilde{B} = (B, B', B'')_{LR}$, then multiplication of these numbers can be carried out as follows (Allahviranloo et al., 2007):

$$\tilde{A} \otimes \tilde{B} = (A, A', A'')_{LR} \otimes (B, B', B'')_{LR} = (A.B, A.B' + B.A', A.B'' + B.A'') \quad (3.35)$$

The crisp equivalent form of the stated FFRLND model can be provided as in Table 3.9 by making use of Allahviranloo et al.'s (2008) method.

3.5.2 Kumar et al.'s (2010) and (2011) Fuzzy Ranking Based Method

Kumar et al. (2010) proposed a method based on a fuzzy ranking procedure for FFLP problems with both equality inequality constraints. They emphasized that the fuzzy optimal solution of a FFLP problem can be easily obtained via the proposed method (Kumar et al., 2011). Apart from the method of Allahviranloo et al., (2008), a triangular fuzzy number and ranking function are defined as follows:

Definition 3.5.2. A fuzzy number $\tilde{A} = (a, b, c)$ is called a triangular fuzzy number if its membership function is described as in the following form:

$$\mu_{\tilde{A}}(x) = \begin{cases} 1 - \frac{x-a}{b-a} & a \leq x \leq b \\ 1 - \frac{x-c}{b-c} & b \leq x \leq c \\ 0 & \text{Otherwise} \end{cases} \quad (3.36)$$

Table 3.9 Transformation process for the FFRLND problem using Allahviranloo et al.'s (2008) method

$$\begin{aligned}
 \text{Min } Z = & \sum_{i=1}^I (f1_{i1} - 0.25.f1_{i2} + 0.25.f1_{i3}).y1_i + \sum_{j=1}^J (f2_{j1} - 0.25.f2_{j2} + 0.25.f2_{j3}).y2_j + \\
 & \sum_{l=1}^L \sum_{i=1}^I (c1_{li1} - 0.25.c1_{li2} + 0.25.c1_{li3}).x_{li1} - \sum_{l=1}^L \sum_{i=1}^I 0.25.c1_{li1}.x_{li2} + \sum_{l=1}^L \sum_{i=1}^I 0.25.c1_{li1}.x_{li3} + \\
 & \sum_{j=1}^J \sum_{i=1}^I (c2_{ij1} - 0.25.c2_{ij2} + 0.25.c2_{ij3}).z_{ij1} - \sum_{j=1}^J \sum_{i=1}^I 0.25.c2_{ij1}.z_{ij2} + \sum_{j=1}^J \sum_{i=1}^I 0.25.c2_{ij1}.z_{ij3} + \\
 & \sum_{k=1}^K \sum_{i=1}^I (c3_{ik1} - 0.25.c3_{ik2} + 0.25.c3_{ik3}).w_{ik1} - \sum_{k=1}^K \sum_{i=1}^I 0.25.c3_{ik1}.w_{ik2} + \sum_{k=1}^K \sum_{i=1}^I 0.25.c3_{ik1}.w_{ik3} + \\
 & \sum_{j=1}^J \sum_{m=1}^M (c4_{jm1} - 0.25.c4_{jm2} + 0.25.c4_{jm3}).v_{jm1} - \sum_{j=1}^J \sum_{m=1}^M 0.25.c4_{jm1}.v_{jm2} + \sum_{j=1}^J \sum_{m=1}^M 0.25.c4_{jm1}.v_{jm3} \\
 \text{Subject to:} \\
 & \sum_{i=1}^I x_{li1} - 0.25.x_{li2} + 0.25.x_{li3} = Re_{l1} - 0.25.Re_{l2} + 0.25.Re_{l3} \quad \forall l \in L \\
 & \sum_{j=1}^J z_{ij1} - 0.25.z_{ij2} + 0.25.z_{ij3} = \{1 - (\gamma_1 - 0.25.\gamma_2 + 0.25.\gamma_3)\} \cdot \sum_{l=1}^L x_{li1} - \\
 & 0.25.(1 - \gamma_1) \cdot \sum_{l=1}^L x_{li2} + 0.25.(1 - \gamma_1) \cdot \sum_{l=1}^L x_{li3} \quad \forall i \in I \\
 & \sum_{k=1}^K w_{ik1} - 0.25.w_{ik2} + 0.25.w_{ik3} = (\gamma_1 - 0.25.\gamma_2 + 0.25.\gamma_3) \cdot \sum_{l=1}^L x_{li1} - \\
 & 0.25.(\gamma_1) \cdot \sum_{l=1}^L x_{li2} + 0.25.(\gamma_1) \cdot \sum_{l=1}^L x_{li3} \quad \forall i \in I \\
 & Stv1_t = we_t.cont_t \quad t = 1; \quad Stv1_t = we_{t-1}.cont_t + we_t.cont_{t-1} \quad t = 2; \\
 & Stv1_t = we_{t-2}.cont_t + we_t.cont_{t-2} \quad t = 3 \\
 & Stv2_{jt} = \alpha_{jt}.Stv1_t \quad t = 1; \quad Stv2_{jt} = \alpha_{jt-1}.Stv1_t + \alpha_{jt}.Stv1_{t-1} \quad t = 2; \\
 & Stv2_{jt} = \alpha_{jt-2}.Stv1_t + \alpha_{jt}.Stv1_{t-2} \quad t = 3 \\
 & \sum_{m=1}^M v_{jm1} - 0.25.v_{jm2} + 0.25.v_{jm3} = \sum_{i=1}^I z_{ij1}.Stv2_{j1} - \sum_{i=1}^I z_{ij2}.0.25.Stv2_{j1} + \sum_{i=1}^I z_{ij3}.0.25.Stv2_{j1} \quad \forall j \in J \\
 & \sum_{l=1}^L x_{li1} - 0.25.x_{li2} + x_{li3} \leq (Cap1_{i1} - 0.25.Cap1_{i2} + Cap1_{i3}).y1_i \quad \forall i \in I \\
 & \sum_{i=1}^I z_{ij1} - 0.25.z_{ij2} + 0.25.z_{ij3} \leq (Cap2_{j1} - 0.25.Cap2_{j2} + 0.25.Cap2_{j3}).y2_j \quad \forall j \in J \\
 & \sum_{i=1}^I w_{ik1} - 0.25.w_{ik2} + 0.25.w_{ik3} \leq Cap3_{k1} - 0.25.Cap3_{k2} + 0.25.Cap3_{k3} \quad \forall k \in K \\
 & \sum_{j=1}^J v_{jm1} - 0.25.v_{jm2} + 0.25.v_{jm3} \leq Cap4_{m1} - 0.25.Cap4_{m2} + 0.25.Cap4_{m3} \quad \forall m \in M \\
 & \sum_{m=1}^M v_{jm1} - 0.25.v_{jm2} + 0.25.v_{jm3} \leq 9.10^8.y2_j \quad \forall j \in J \\
 & y1_i, y2_j \in (0,1) \quad \forall i \in I, j \in J \\
 & x_{li1} \geq x_{li2} \quad x_{li1} + 0.25.x_{li3} \geq 0.25.x_{li2} \quad \forall i \in I, \forall l \in L \\
 & z_{ij1} \geq z_{ij2} \quad z_{ij1} + 0.25.z_{ij3} \geq 0.25.z_{ij2} \quad \forall i \in I, \forall j \in J \\
 & w_{ik1} \geq w_{ik2} \quad w_{ik1} + 0.25.w_{ik3} \geq 0.25.w_{ik2} \quad \forall i \in I, \forall k \in K \\
 & v_{jm1} \geq v_{jm2} \quad v_{jm1} + 0.25.v_{jm3} \geq 0.25.v_{jm2} \quad \forall j \in J, \forall m \in M
 \end{aligned}$$

Definition 3.5.3. The ranking function based on comparison of the expected values of the triangular fuzzy numbers can be defined for any fuzzy number, $\tilde{A} = (a, b, c)$ as follows:

$$\Re(\tilde{A}) = \frac{a + 2b + c}{4} \quad (3.37)$$

In detail, the above fuzzy ranking function is used by that method so as to defuzzify the objective function coefficients. According to this method, if the examined FFLP problem has inequality constraints, first of all, these constraints should be converted into equality constraints by introducing non-negative variables to the left or right side of the constraints. The two different cases for inequality constraints are expressed as follows:

Case 1: $\lesssim$ type constraints; $\sum_{j=1}^n \tilde{a}_{ij} \otimes \tilde{x}_j \lesssim \tilde{b}_i$, convert such constraints into equality form:

$$\sum_{j=1}^n \tilde{a}_{ij} \otimes \tilde{x}_j \oplus \tilde{S}_i = \tilde{b}_i \quad \forall i \in m \quad (3.38)$$

Case 2: $\gtrsim$ type constraints; $\sum_{j=1}^n \tilde{a}_{ij} \otimes \tilde{x}_j \gtrsim \tilde{b}_i$, convert such constraints into equality form :

$$\sum_{j=1}^n \tilde{a}_{ij} \otimes \tilde{x}_j = \tilde{b}_i \oplus \tilde{S}_i \quad \forall i \in m \quad (3.39)$$

where $\tilde{S}_i$ is a non-negative fuzzy number. The details of this method can be summarized through the following steps:

Step 1: Convert the inequality constraints into the equality form and obtain the following FFLP problem:

$$\text{Max or Min } \tilde{C}^T \otimes \tilde{X} \quad (3.40)$$

$$\text{Subject to; } \tilde{A} \otimes \tilde{X} = \tilde{B} \quad (3.41)$$

where $\tilde{X}$ is a non-negative fuzzy number, $\tilde{C}^T = [\tilde{c}_j]_{1 \times n}$, $\tilde{X} = [\tilde{x}_j]_{n \times 1}$, $\tilde{A} = [\tilde{a}_{ij}]_{m \times n}$, $\tilde{B} = [\tilde{b}_i]_{m \times 1}$. Thus, the problem can also be written as follows:

$$\text{Max or Min } \sum_{j=1}^n \tilde{c}_j \otimes \tilde{x}_j \quad (3.42)$$

$$\text{Subject to; } \sum_{j=1}^n \tilde{a}_{ij} \otimes \tilde{x}_j = \tilde{b}_i \quad \forall i \in m \quad (3.43)$$

Step 2: If all of the parameters and the decision variables ($\tilde{c}_j$, $\tilde{x}_j$, $\tilde{a}_{ij}$ and $\tilde{b}_i$) are represented by the triangular fuzzy numbers (p_j, q_j, r_j) , (x_j, y_j, z_j) , (a_{ij}, b_{ij}, c_{ij}) and (b_i, g_i, h_i) , the above FFLP problem can presented as follows:

$$\text{Max or Min } \sum_{j=1}^n (p_j, q_j, r_j) \otimes (x_j, y_j, z_j) \quad (3.44)$$

$$\text{Subject to; } \sum_{j=1}^n (a_{ij}, b_{ij}, c_{ij}) \otimes (x_j, y_j, z_j) = (b_i, g_i, h_i) \quad \forall i \in m \quad (3.45)$$

$$(x_j, y_j, z_j) \text{ is a non-negative triangular fuzzy number.} \quad (3.46)$$

Step 3: After performing the fuzzy multiplication operation $(a_{ij}, b_{ij}, c_{ij}) \otimes (x_j, y_j, z_j) = (m_{ij}, n_{ij}, o_{ij})$ and applying the previously formulated fuzzy ranking procedure, the following model can be yielded:

$$\text{Max or Min } \Re \left(\sum_{j=1}^n (p_j, q_j, r_j) \otimes (x_j, y_j, z_j) \right) \quad (3.47)$$

$$\text{Subject to; } \sum_{j=1}^n (m_{ij}, n_{ij}, o_{ij}) = (b_i, g_i, h_i) \quad \forall i \in m \quad (3.48)$$

$$(x_j, y_j, z_j) \text{ is a non-negative triangular fuzzy number.} \quad (3.49)$$

Step 4: Finally, the following crisp LP problem can be provided after performing the transformation process by using standard fuzzy arithmetic operations:

$$\text{Max or Min } \Re \left(\sum_{j=1}^n (p_j, q_j, r_j) \otimes (x_j, y_j, z_j) \right) \quad (3.50)$$

$$\sum_{j=1}^n m_{ij} = b_i \quad \forall i \in m \quad (3.51)$$

$$\sum_{j=1}^n n_{ij} = g_i \quad \forall i \in m \quad (3.52)$$

$$\sum_{j=1}^n o_{ij} = h_i \quad \forall i \in m \quad (3.53)$$

$$y_j - x_j \geq 0 \text{ and } z_j - y_j \geq 0 \quad \forall j \in n \quad (3.54)$$

Najafi and Edalatpanah (2013) made some corrections on this method by adding the following constraint set: $x_j \geq 0 \quad \forall j \in n$. Ultimately, the solution of the above crisp LP problem can be found by using an optimization software and then the fuzzy objective function value can be obtained by substituting $\tilde{x}_j$ in $\sum_j \tilde{c}_j \otimes \tilde{x}_j$.

The examined FFRLND model which is presented in Section 3.3.3 can be transformed into the crisp equivalent form via the method of Kumar et al. (2010) and (2011) as in Table 3.10. In that Table, index $n = 1, 2$ and 3 represent the pessimistic, most likely and optimistic values of a triangular fuzzy number, respectively. For each fuzzy parameter and decision variable, this additional index is utilized.

3.5.3 Jayalakshmi and Pandian's (2012) Bound and Decomposition Method

In order to find the fuzzy efficient solution of a FFLP problem, Jayalakshmi and Pandian (2012) proposed a method which does not require usage of any ranking function and addition of auxiliary non-negative fuzzy variables. Moreover, there is no limitation on the elements of the coefficient matrix in this method. Actually, this method depends on the decomposition of any given FFLP problem into the three crisp LP problems with bounded variables and constraints while dealing with triangular fuzzy numbers. In the case of trapezoidal fuzzy numbers and variables, the decision maker(s) should decompose the FFLP problem into the four crisp LP problems. After the decomposition process, the crisp LP problems should be solved separately and the fuzzy efficient solution of the FFLP problem can be provided by utilizing their solutions as bounded variables. The details of this method can be summarized through the following steps:

Step 1: By using the fuzzy arithmetic operations and partial ordering relations, generate middle level, upper level and lower level problems (Decomposition stage).

Table 3.10 Transformation process for FFRLND problem using Kumar et al.'s (2011) method

$$\begin{aligned}
 \text{Min } Z = & \frac{1}{4} \cdot \left\{ \sum_{i=1}^I f1_{i1} \cdot y1_i + \sum_{j=1}^J f2_{j1} \cdot y2_j + \sum_{l=1}^L \sum_{i=1}^I c1_{li1} \cdot x_{li1} + \sum_{i=1}^I \sum_{j=1}^J c2_{ij1} \cdot z_{ij1} + \sum_{i=1}^I \sum_{k=1}^K c3_{ik1} \cdot w_{ik1} + \right. \\
 & \sum_{j=1}^J \sum_{m=1}^M c4_{jm1} \cdot v_{jm1} + 2 \cdot \left(\sum_{i=1}^I f1_{i2} \cdot y1_i + \sum_{j=1}^J f2_{j2} \cdot y2_j + \sum_{l=1}^L \sum_{i=1}^I c1_{li2} \cdot x_{li2} + \sum_{i=1}^I \sum_{j=1}^J c2_{ij2} \cdot z_{ij2} + \right. \\
 & \left. \sum_{i=1}^I \sum_{k=1}^K c3_{ik2} \cdot w_{ik2} + \sum_{j=1}^J \sum_{m=1}^M c4_{jm2} \cdot v_{jm2} \right) + \sum_{i=1}^I f1_{i3} \cdot y1_i + \sum_{j=1}^J f2_{j3} \cdot y2_j + \sum_{l=1}^L \sum_{i=1}^I c1_{li3} \cdot x_{li3} + \\
 & \left. \sum_{i=1}^I \sum_{j=1}^J c2_{ij3} \cdot z_{ij3} + \sum_{i=1}^I \sum_{k=1}^K c3_{ik3} \cdot w_{ik3} + \sum_{j=1}^J \sum_{m=1}^M c4_{jm3} \cdot v_{jm3} \right\} \\
 \text{Subject to;} \\
 & \sum_{i=1}^I x_{lin} = Re_{ln} + s1_{ln} \quad \forall l \in L, \forall n \in N \\
 & \sum_{j=1}^J z_{ijn} = (1 - \gamma_n) \cdot \sum_{l=1}^L x_{lin} \quad \forall i \in I, n = 2 \\
 & \sum_{j=1}^J z_{ijn} = (1 - \gamma_{n+2}) \cdot \sum_{l=1}^L x_{lin} \quad \forall i \in I, n = 1 \\
 & \sum_{j=1}^J z_{ijn} = (1 - \gamma_{n-2}) \cdot \sum_{l=1}^L x_{lin} \quad \forall i \in I, n = 3 \\
 & \sum_{k=1}^K w_{ikn} = \gamma_n \cdot \sum_{l=1}^L x_{lin} \quad \forall i \in I, \forall n \in N \\
 & \sum_{m=1}^M v_{jmn} = \sum_{i=1}^I z_{ijn} \cdot we_n \cdot cont_n \cdot \alpha_{jn} \quad \forall j \in J, \forall n \in N \\
 & \sum_{l=1}^L x_{lin} + s2_{in} = Cap1_{in} \cdot y1_i \quad \forall i \in I, \forall n \in N \\
 & \sum_{i=1}^I z_{ijn} + s3_{jn} = Cap2_{jn} \cdot y2_j \quad \forall j \in J, \forall n \in N \\
 & \sum_{i=1}^I w_{ikn} + s4_{kn} = Cap3_{kn} \quad \forall k \in K, \forall n \in N \\
 & \sum_{j=1}^J v_{jmn} + s5_{mn} = Cap4_{mn} \quad \forall m \in M, \forall n \in N \\
 & \sum_{m=1}^M v_{jmn} + s6_{jn} = 9 \cdot 10^7 \cdot y2_j \quad \forall j \in J, n = 1 \\
 & \sum_{m=1}^M v_{jmn} + s6_{jn} = 9 \cdot 10^8 \cdot y2_j \quad \forall j \in J, n = 2 \\
 & \sum_{m=1}^M v_{jmn} + s6_{jn} = 9 \cdot 10^9 \cdot y2_j \quad \forall j \in J, n = 3 \\
 & y1_i, y2_j \in (0,1) \quad \forall i \in I, \forall j \in J \\
 & x_{li3} \geq x_{li2} \quad x_{li2} \geq x_{li1} \quad \forall l \in L, \forall i \in I \\
 & z_{ij3} \geq z_{ij2} \quad z_{ij2} \geq z_{ij1} \quad \forall i \in I, \forall j \in J \\
 & w_{ik3} \geq w_{ik2} \quad w_{ik2} \geq w_{ik1} \quad \forall i \in I, \forall k \in K \\
 & v_{jm3} \geq v_{jm2} \quad v_{jm2} \geq v_{jm1} \quad \forall j \in J, \forall m \in M \\
 & s1_{l3} \geq s1_{l2} \quad s1_{l2} \geq s1_{l1} \quad \forall l \in L; \quad s2_{i3} \geq s2_{j2} \quad s2_{i2} \geq s2_{j1} \quad \forall j \in J \\
 & s3_{j3} \geq s3_{j2} \quad s3_{j2} \geq s3_{j1} \quad \forall k \in K; \quad s4_{k3} \geq s4_{k2} \quad s4_{k2} \geq s4_{k1} \quad \forall m \in M \\
 & s5_{m3} \geq s5_{j2} \quad s5_{m2} \geq s5_{m1} \quad \forall j \in J; \quad s6_{j3} \geq s6_{j2} \quad s6_{j2} \geq s6_{j1} \quad \forall j \in J
 \end{aligned}$$

$$\text{Max or Min } \tilde{Z}_1 \cong \sum_{j=1}^n \text{Lower value of } ((p_j, q_j, r_j) \otimes (x_j, y_j, z_j)) \quad (3.55)$$

$$\text{Max or Min } \tilde{Z}_2 \cong \sum_{j=1}^n \text{Middle value of } ((p_j, q_j, r_j) \otimes (x_j, y_j, z_j)) \quad (3.56)$$

$$\text{Max or Min } \tilde{Z}_3 \cong \sum_{j=1}^n \text{Upper value of } ((p_j, q_j, r_j) \otimes (x_j, y_j, z_j)) \quad (3.57)$$

$$\sum_{j=1}^n \text{Lower value of } ((a_{ij}, b_{ij}, c_{ij}) \otimes (x_j, y_j, z_j)) \{ \lesssim, \approx, \gtrsim \} b_i \quad \forall i \in m \quad (3.58)$$

$$\sum_{j=1}^n \text{Middle value of } ((a_{ij}, b_{ij}, c_{ij}) \otimes (x_j, y_j, z_j)) \{ \lesssim, \approx, \gtrsim \} g_i \quad \forall i \in m \quad (3.59)$$

$$\sum_{j=1}^n \text{Upper value of } ((a_{ij}, b_{ij}, c_{ij}) \otimes (x_j, y_j, z_j)) \{ \lesssim, \approx, \gtrsim \} h_i \quad \forall i \in m \quad (3.60)$$

$$(x_j, y_j, z_j) \text{ is a non-negative triangular fuzzy number.} \quad (3.61)$$

Step 2: First, solve the middle level problem in which at least one decision variable of the middle level problem exists into the constraints.

Step 3: Then, solve the upper level problem in which at least one decision variable of this upper level problem occurs into the constraints and should not take place in the middle level problem. Before solving the upper level problem, replace the values of the decision variables with the obtained values from the middle level problem. The upper level problem should also satisfy the following bounded constraint:

$$\sum_{j=1}^n \text{Upper value of } ((p_j, q_j, r_j) \otimes (x_j, y_j, z_j)) \geq Z_2^* \quad (3.62)$$

Step 4: Then, solve the lower level problem in which at least one decision variable of this lower level problem occurs into the constraints and should not take place in both of the middle level problem and upper level problems. Before solving the lower level problem, replace the values of the decision variables with the obtained values from the middle and upper level problems. The lower level problem should also satisfy the following bounded constraint:

$$\sum_{j=1}^n \text{Lower value of } ((p_j, q_j, r_j) \otimes (x_j, y_j, z_j)) \leq Z_2^* \quad (3.63)$$

where Z_2^* is the optimal objective value of the middle level problem.

Step 5: Obtain the fuzzy efficient solution (x_j^*, y_j^*, z_j^*) and the maximum or (minimum) fuzzy objective values (Z_1^*, Z_2^*, Z_3^*) from the solutions of the lower, middle and upper level problems.

The examined FFRLND problem can be converted into crisp equivalent form using the bound and decomposition method as in Tables 3.11 - 3.13. Similar to method of Kumar et al. (2010) and (2011), additional index n is utilized for each parameter and decision variable which is represented by triangular fuzzy numbers. While decomposing the problem, middle level problem can be constructed as in Table 3.11.

Table 3.11 The middle level problem for FFRLND problem using bound and decomposition method

$$\begin{aligned} \text{Min } Z_2 = & \sum_{i=1}^I f1_{i2} \cdot y1_i + \sum_{j=1}^J f2_{j2} \cdot y2_j + \sum_{l=1}^L \sum_{i=1}^I c1_{li2} \cdot x_{li2} + \sum_{i=1}^I \sum_{j=1}^J c2_{ij2} \cdot z_{ij2} + \sum_{i=1}^I \sum_{k=1}^K c3_{ik2} \cdot w_{ik2} + \\ & \sum_{j=1}^J \sum_{m=1}^M c4_{jm2} \cdot v_{jm2} \end{aligned}$$

Subject to;

$$\begin{aligned} \sum_{i=1}^I x_{li2} & \geq Re_{l2} & \forall l \in L \\ \sum_{j=1}^J z_{ij2} & = (1 - \gamma_2) \cdot \sum_{l=1}^L x_{li2} & \forall i \in I \\ \sum_{k=1}^K w_{ik2} & = \gamma_2 \cdot \sum_{l=1}^L x_{li2} & \forall i \in I \\ \sum_{m=1}^M v_{jm2} & = \sum_{i=1}^I z_{ij2} \cdot we_2 \cdot cont_2 \cdot \alpha_{j2} & \forall j \in J \\ \sum_{l=1}^L x_{li2} & \leq Cap1_{i2} \cdot y1_i & \forall i \in I \\ \sum_{i=1}^I z_{ij2} & \leq Cap2_{j2} \cdot y2_j & \forall j \in J \\ \sum_{i=1}^I w_{ik2} & \leq Cap3_{k2} & \forall k \in K \\ \sum_{j=1}^J v_{jm2} & \leq Cap4_{m2} & \forall m \in M \\ \sum_{m=1}^M v_{jm2} & \leq 9 \cdot 10^8 \cdot y2_j & \forall j \in J \\ y1_i, y2_j & \in (0,1) & \forall i \in I, \forall j \in J \end{aligned}$$

All other variables are continuous and non – negative.

After solving the middle level problem with the given data in Section 3.6, the upper level problem can be formulated as in the following Table 3.12.

Table 3.12 The upper level problem for the FFRLND problem using bound and decomposition method

$$\begin{aligned} \text{Min } Z_3 = & \sum_{i=1}^I f1_{i3} \cdot y1_i + \sum_{j=1}^J f2_{j3} \cdot y2_j + \sum_{l=1}^L \sum_{i=1}^I c1_{li3} \cdot x_{li3} + \sum_{i=1}^I \sum_{j=1}^J c2_{ij3} \cdot z_{ij3} + \sum_{i=1}^I \sum_{k=1}^K c3_{ik3} \cdot w_{ik3} + \\ & \sum_{j=1}^J \sum_{m=1}^M c5_{jm3} \cdot v_{jm3} \end{aligned}$$

Subject to;

$$Z_3 \geq 1015304$$

$$\sum_{l=1}^L x_{li3} \geq Re_{l3} \quad \forall l \in L$$

$$\sum_{j=1}^J z_{ij3} = (1 - \gamma_1) \cdot \sum_{l=1}^L x_{li3} \quad \forall i \in I$$

$$\sum_{k=1}^K w_{ik3} = \gamma_3 \cdot \sum_{l=1}^L x_{li3} \quad \forall i \in I$$

$$\sum_{m=1}^M v_{jm3} = \sum_{i=1}^I z_{ij3} \cdot we_3 \cdot cont_3 \cdot \alpha_{j3} \quad \forall j \in J$$

$$\sum_{l=1}^L x_{li3} \leq Cap1_{i3} \cdot y1_i \quad \forall i \in I$$

$$\sum_{i=1}^I z_{ij3} \leq Cap2_{j3} \cdot y2_j \quad \forall j \in J$$

$$\sum_{i=1}^I w_{ik3} \leq Cap3_{k3} \quad \forall k \in K$$

$$\sum_{j=1}^J v_{jm3} \leq Cap4_{m3} \quad \forall m \in M$$

$$\sum_{m=1}^M v_{jm3} \leq 9 \cdot 10^8 \cdot y2_j \quad \forall j \in J$$

$$y1_i, y2_j \in (0,1) \quad \forall i \in I, \forall j \in J$$

$$y1_1 = 1, \quad y1_2 = 1, \quad y1_3 = 0, \quad y2_1 = 1 \quad \text{and} \quad y2_2 = 1$$

$$x_{113} \geq 300, \quad x_{213} \geq 50, \quad x_{223} \geq 300, \quad x_{313} \geq 300 \quad \text{and} \quad x_{423} \geq 350$$

$$z_{113} \geq 315, \quad z_{123} \geq 270 \quad \text{and} \quad z_{213} \geq 585$$

$$w_{123} \geq 65 \quad \text{and} \quad w_{223} \geq 65$$

$$v_{123} \geq 3780 \quad \text{and} \quad v_{223} \geq 1512$$

All other variables are continuous and non – negative.

Finally, the lower level problem of the stated FFRLND model can be given as in Table 3.13.

Table 3.13 The lower level problem for the FFRLND problem using bound and decomposition method

$$\begin{aligned} \text{Min } Z_1 = & \sum_{i=1}^I f1_{i1} \cdot y1_i + \sum_{j=1}^J f2_{j1} \cdot y2_j + \sum_{l=1}^L \sum_{i=1}^I c1_{li1} \cdot x_{li1} + \sum_{i=1}^I \sum_{j=1}^J c2_{ij1} \cdot z_{ij1} + \sum_{i=1}^I \sum_{k=1}^K c3_{ik1} \cdot w_{ik1} + \\ & \sum_{j=1}^J \sum_{m=1}^M c5_{jm1} \cdot v_{jm1} \end{aligned}$$

Subject to;

$$Z_1 \leq 1015304$$

$$\sum_{i=1}^I x_{li1} \geq Re_{l1} \quad \forall l \in L$$

$$\sum_{j=1}^J z_{ij1} = (1 - \gamma_3) \cdot \sum_{l=1}^L x_{li1} \quad \forall i \in I$$

$$\sum_{k=1}^K w_{ik1} = \gamma_1 \cdot \sum_{l=1}^L x_{li1} \quad \forall i \in I$$

$$\sum_{m=1}^M v_{jm1} = \sum_{i=1}^I z_{ij1} \cdot we_1 \cdot cont_1 \cdot \alpha_{j1} \quad \forall j \in J$$

$$\sum_{l=1}^L x_{li1} \leq Cap1_{i1} \cdot y1_i \quad \forall i \in I$$

$$\sum_{i=1}^I z_{ij1} \leq Cap2_{j1} \cdot y2_j \quad \forall j \in J$$

$$\sum_{i=1}^I w_{ik1} \leq Cap3_{k1} \quad \forall k \in K$$

$$\sum_{j=1}^J v_{jm1} \leq Cap4_{m1} \quad \forall m \in M$$

$$\sum_{m=1}^M v_{jm1} \leq 9 \cdot 10^8 \cdot y2_j \quad \forall j \in J$$

$$y1_i, y2_j \in (0,1) \quad \forall i \in I, \forall j \in J$$

$$y1_1 = 1, \quad y1_2 = 1, \quad y1_3 = 0, \quad y2_1 = 1 \quad \text{and} \quad y2_2 = 1$$

$$x_{111} \leq 300, \quad x_{211} \leq 50, \quad x_{221} \leq 300, \quad x_{311} \leq 300 \quad \text{and} \quad x_{421} \leq 350$$

$$z_{111} \leq 315, \quad z_{121} \leq 270 \quad \text{and} \quad z_{211} \leq 585$$

$$w_{121} \leq 65 \quad \text{and} \quad w_{221} \leq 65$$

$$v_{121} \leq 3780 \quad \text{and} \quad v_{221} \leq 1512$$

$$x_{121} \leq 0, \quad x_{131} \leq 0, \quad x_{231} \leq 0, \quad x_{321} \leq 0, \quad x_{331} \leq 0, \quad x_{411} \leq 0 \quad \text{and} \quad x_{431} \leq 0$$

$$z_{221} \leq 0, \quad z_{311} \leq 0 \quad \text{and} \quad z_{321} \leq 0$$

$$w_{111} \leq 0, \quad w_{211} \leq 0, \quad w_{311} \leq 0 \quad \text{and} \quad w_{321} \leq 0$$

$$v_{111} \leq 0 \quad \text{and} \quad v_{211} \leq 0$$

All other variables are continuous and non – negative.

3.5.4 The Proposed (α, β) -Parametric Method with Risk Consideration

Both of the aforementioned methods mainly depend on Zadeh's (1975) extension principle which is one of the most important tools in fuzzy set theory. However, in some occasions, these methods may not generate applicable or realizable solutions for

some engineering optimization problems. Because, the standard fuzzy arithmetic operations utilized by these methods may produce some counterintuitive results (Klir, 1997). In other words, the most commonly used methods including standard fuzzy arithmetic operations may produce risky solutions and questionable results for many real world cases. In detail, while realizing the solutions provided by these methods, infeasibility and/or inapplicability problems may arise because of the negative part of the fuzzy remaining capacity of the facilities (*for $\lesssim$ type constraints*) and positive part of the fuzzy remaining demand of the customers (*for $\gtrsim$ type constraints*). Actually, the risks of unsatisfactory demand or unavailable capacity may arise while realizing the provided fuzzy solutions in a transportation network under fully uncertain environments. Thus, generated solutions by these former methods may not be appropriate for a risk-averse decision maker. Therefore, these solutions for any given FFLP cannot correspond to the fuzzy optimal solutions as emphasized by the previous papers. In order to obtain applicable and realizable fuzzy solutions for a risk-averse person, additional constraints should be added to maintain that the remaining capacities of the sources will be non-negative fuzzy numbers and the demands will be fully satisfied. Alternatively, the decision maker may not be entirely risk-averse and may want to take risk in a certain level according to his/her risk tolerance. For all of these reasons, a new transformation method is required for solving FFLP problems while taking into account the risk attitude of the decision maker. This is essential for the decision making process in a fully fuzzy environment. Therefore, a new (α, β) -parametric method is presented in this chapter for solving mathematical programs with fuzzy decision variables. The proposed method is based on α -cuts (it is an alpha parametric model) so it is able to consider various uncertainty levels.

Remark 3.5.1. Many usual principles for operation on real numbers don't extend to standard fuzzy arithmetic as it is seen from the followings (Gani & Assarudeen, 2012):

$$\tilde{A} \ominus \tilde{A} \neq 0 \quad (3.64)$$

$$\text{If } \tilde{A} \oplus \tilde{B} = \tilde{C}, \text{ then } \tilde{B} \neq \tilde{C} \ominus \tilde{A} \quad (3.65)$$

$$\text{If } \tilde{A} \otimes \tilde{B} = \tilde{C}, \text{ then } \tilde{B} \neq \tilde{C} \oslash \tilde{A} \quad (3.66)$$

where $\tilde{C}$ is fuzzy solution of the fuzzy linear equation. In fact, addition and subtraction (respectively, multiplication and division) operations are not reciprocal for fuzzy

numbers. In other words, it is not possible to solve inverse problems exactly using the standard fuzzy arithmetic operators (Boukezzoula et al., 2014; Gani & Assarudeen, 2012). Therefore, some counterintuitive results may arise for many practical applications. For that reason, additional information such as attitude of decision maker(s)' toward risk is required so as to provide appropriate solutions for FFLP problems according to his/her risk sensitivity. This can be realized by the inclusion of additional constraints into the crisp equivalent model.

Definition 3.5.4. In the proposed parametric method, operations are defined on α -cut representation of fuzzy intervals (Klir, 1997). So, α -cuts of a triangular fuzzy number, $\tilde{A} = (a, b, c)$ can be denoted for all $\alpha \in (0, 1]$ by the following formula:

$$A^\alpha = [a + (b - a)\alpha, c - (c - b)\alpha] \quad (3.67)$$

Remark 3.5.2. Each fuzzy number can be characterized in terms of a base variable. The actual value of the base variable associated to a linguistic variable is approximated by the fuzzy numbers. For example, given any pair of linguistic variables, A and B , defined for base variables a and b , respectively. The values of these base variables are in the set of real numbers $\mathbb{R}$ (Klir & Cooper, 1996; Klir & Pan, 1998).

In the proposed method, various fuzzy efficient solutions can be generated according to the different risk sensitivity degrees of the decision maker(s). In detail, when the risk sensitivity of the decision maker(s), i.e., β is equal to 1, there will be a crisp relation between the base variables of the fuzzy components into the examined constraint. This can be illustrated by the following Figure 3.10 for a risk-averse decision maker. In the stated constraint ($\gtrsim$ type), additional constraint $\sum_{j=1}^n \underline{d}_{ij}(\alpha) \otimes \underline{x}_j(\alpha) \geq \overline{e}_i(\alpha)$ should be satisfied instead of the current $\sum_{j=1}^n \underline{d}_{ij}(\alpha) \otimes \underline{x}_j(\alpha) \geq \underline{e}_i(\alpha)$ constraint which is resulted from standard fuzzy arithmetic. Thus, a crisp relation will occur between the base variables of the corresponding fuzzy numbers $(\sum_j d_{ij} \cdot x_j \geq e_i)$. On the other hand, when β is equal to zero (in the case of a risk-seeking), there will be an equality constraint among the base variables of the fuzzy components and the following constraint: $\sum_{j=1}^n \underline{d}_{ij}(\alpha) \otimes \underline{x}_j(\alpha) \geq \underline{e}_i(\alpha)$ will be active. Besides, it is possible to obtain various

fuzzy efficient solutions when this risk sensitivity degree took different values in the interval of $[0, 1]$. Actually, this corresponds to the partially risk-averse decision maker(s) and partially risk-seekers and also generates a fuzzy relation between the base variables of the fuzzy components. Similar explanations are also valid for ($\lesssim$ type) constraint which is depicted by Figure 3.11.

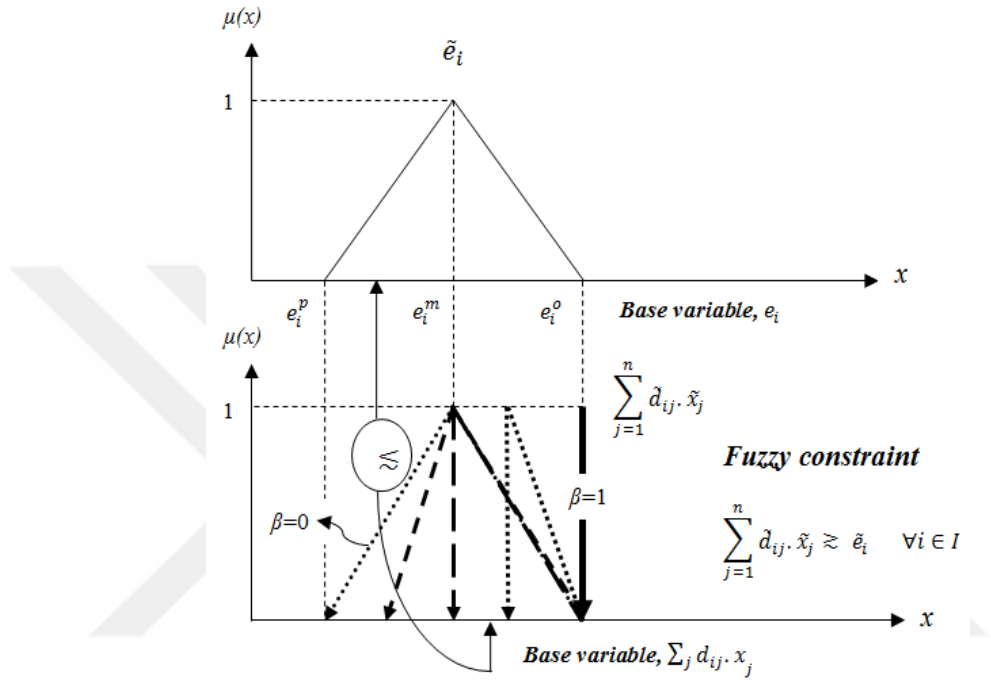


Figure 3.10 The membership functions of the solution for $\geq$ type constraints with different β values

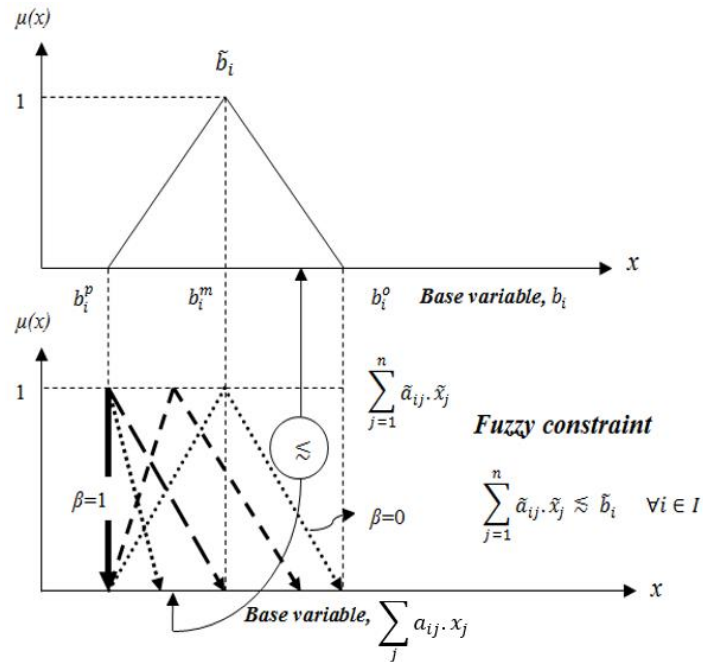


Figure 3.11 The membership functions of the solution for $\leq$ type constraints with different β values

In reality, risk-averse decision maker(s) may not desire to acquire overly imprecise solutions or overestimation into the decision variables. In fact, they prefer crisp and/or risk-free solutions. As it can be seen from Figures 3.10 and 3.11, risk-free and/or risk embedded solutions can be provided by utilizing the proposed method according to the risk sensitivity of decision maker (risk-averse and/or risk-seeker). The fundamentals of the proposed method can be summarized by the following steps on a FFLP model with different types of fuzzy inequalities:

$$\min \text{ or } \max \quad \tilde{z} \cong \sum_{j=1}^n \tilde{c}_j \cdot \tilde{x}_j \quad (3.68)$$

$$\sum_{j=1}^n \tilde{a}_{ij} \cdot \tilde{x}_j \lesssim \tilde{b}_i \quad \forall i \in I \quad (3.69)$$

$$\sum_{j=1}^n \tilde{d}_{ij} \cdot \tilde{x}_j \gtrsim \tilde{e}_i \quad \forall i \in I \quad (3.70)$$

$$\tilde{x}_j \text{ is a non-negative triangular fuzzy number.} \quad (3.71)$$

Step 1: The crisp equivalent form of the previously formulated FFLP model can be written as follows by using results of fuzzy arithmetic operations on fuzzy intervals:

$$\min \text{ or } \max \quad \tilde{z} \cong \left[\sum_{j=1}^n \underline{c}_j(\alpha) \otimes \underline{x}_j(\alpha) + \sum_{j=1}^n \overline{c}_j(\alpha) \otimes \overline{x}_j(\alpha) \right] \quad (3.72)$$

$$\sum_{j=1}^n \underline{a}_{ij}(\alpha) \otimes \underline{x}_j(\alpha) \leq \underline{b}_i(\alpha) \quad \forall i \in I \quad (3.73)$$

$$\sum_{j=1}^n \overline{a}_{ij}(\alpha) \otimes \overline{x}_j(\alpha) \leq \beta \cdot \underline{b}_i(\alpha) + (1 - \beta) \cdot \overline{b}_i(\alpha) \quad \forall i \in I \quad (3.74)$$

$$\sum_{j=1}^n \underline{d}_{ij}(\alpha) \otimes \underline{x}_j(\alpha) \geq \beta \cdot \overline{e}_i(\alpha) + (1 - \beta) \cdot \underline{e}_i(\alpha) \quad \forall i \in I \quad (3.75)$$

$$\sum_{j=1}^n \overline{d}_{ij}(\alpha) \otimes \overline{x}_j(\alpha) \geq \overline{e}_i(\alpha) \quad \forall i \in I \quad (3.76)$$

$$\underline{x}_j(\alpha) \geq 0 \quad \text{and} \quad \overline{x}_j(\alpha) \geq 0 \quad \forall j \in J \quad (3.77)$$

Step 2: The problem may also be written as followings by substituting the α -cut representation of the fuzzy numbers into the end points which are given in the step-1:

$$\begin{aligned} \min \text{ or } \max \quad Z = & \left[\sum_{j=1}^n (c_j^p + (c_j^m - c_j^p)\alpha) \cdot (x_j^p + (x_j^m - x_j^p)\alpha) \right. \\ & \left. + \sum_{j=1}^n (c_j^o - (c_j^o - c_j^m)\alpha) \cdot (x_j^o - (x_j^o - x_j^m)\alpha) \right] \end{aligned} \quad (3.78)$$

$$\sum_{j=1}^n (a_{ij}^p + (a_{ij}^m - a_{ij}^p)\alpha) \cdot (x_j^p + (x_j^m - x_j^p)\alpha) \leq (b_i^p + (b_i^m - b_i^p)\alpha) \quad \forall i \in I \quad (3.79)$$

$$\begin{aligned} & \sum_{j=1}^n (a_{ij}^o - (a_{ij}^o - a_{ij}^m)\alpha) \cdot (x_j^o - (x_j^o - x_j^m)\alpha) \\ & \leq \beta \cdot (b_i^p + (b_i^m - b_i^p)\alpha) + (1 - \beta) \cdot (b_i^o - (b_i^o - b_i^m)\alpha) \quad \forall i \in I \end{aligned} \quad (3.80)$$

$$\begin{aligned} & \sum_{j=1}^n (d_{ij}^p + (d_{ij}^m - d_{ij}^p)\alpha) \cdot (x_j^p + (x_j^m - x_j^p)\alpha) \\ & \geq \beta \cdot (e_i^o - (e_i^o - e_i^m)\alpha) + (1 - \beta) \cdot (e_i^p + (e_i^m - e_i^p)\alpha) \quad \forall i \in I \end{aligned} \quad (3.81)$$

$$\sum_{j=1}^n (d_{ij}^o - (d_{ij}^o - d_{ij}^m)\alpha) \cdot (x_j^o - (x_j^o - x_j^m)\alpha) \geq (e_i^o - (e_i^o - e_i^m)\alpha) \quad \forall i \in I \quad (3.82)$$

$$x_j^o \geq x_j^m, \quad x_j^m \geq x_j^p, \quad x_j^p \geq 0 \quad \forall j \in J \quad (3.83)$$

where $\beta \in [0, 1]$ represents the degree of risk-sensitivity or risk tolerance of the decision maker(s). In light of the foregoing, the stated FFRLND problem can be transformed into the crisp equivalent form by utilizing the proposed method as in Table 3.14. Since the proposed method mainly based on the α -cut representation of fuzzy intervals, superscripts, i.e., p , m and o which display the pessimistic, most likely and optimistic values of the uncertain parameters or variables which are represented by triangular fuzzy numbers, are utilized. For each fuzzy parameter and decision variable, this additional superscript is used.

In addition, as emphasized by Wu, Lu, and Zhang (2004) and (2006), development of a decision support system may also be needed to support the general decision maker's decision making process effectively in a RL network design. For this reason, an architecture for a decision support system which contains the proposed parametric method is presented in Figure 3.12. Actually, this decision support system may consist of four components.

Table 3.14 Transformation process for the FFRLND problem by using the proposed method

$$\begin{aligned}
 \text{Min } Z = & \sum_i^I (f1_i^p + (f1_i^m - f1_i^p) \cdot \alpha) \cdot y1_i + \sum_j^J (f2_j^p + (f2_j^m - f2_j^p) \cdot \alpha) \cdot y2_j + \\
 & \sum_i^L \sum_i^I (c1_{li}^p + (c1_{li}^m - c1_{li}^p) \cdot \alpha) \cdot (x_{li}^p + (x_{li}^m - x_{li}^p) \cdot \alpha) + \sum_i^I \sum_j^J (c2_{ij}^p + (c2_{ij}^m - c2_{ij}^p) \cdot \alpha) \cdot (z_{ij}^p + (z_{ij}^m - z_{ij}^p) \cdot \alpha) + \\
 & \sum_i^I \sum_k^K (c3_{ik}^p + (c3_{ik}^m - c3_{ik}^p) \cdot \alpha) \cdot (w_{ik}^p + (w_{ik}^m - w_{ik}^p) \cdot \alpha) + \sum_j^J \sum_m^M (c4_{jm}^p + (c4_{jm}^m - c4_{jm}^p) \cdot \alpha) \cdot (v_{jm}^p + (v_{jm}^m - v_{jm}^p) \cdot \alpha) + \\
 & \sum_i^I (f1_i^o - (f1_i^p - f1_i^m) \cdot \alpha) \cdot y1_i + \sum_j^J (f2_j^o - (f2_j^p - f2_j^m) \cdot \alpha) \cdot y2_j + \\
 & \sum_i^L \sum_i^I (c1_{li}^o - (c1_{li}^p - c1_{li}^m) \cdot \alpha) \cdot (x_{li}^o - (x_{li}^p - x_{li}^m) \cdot \alpha) + \sum_i^I \sum_j^J (c2_{ij}^o - (c2_{ij}^p - c2_{ij}^m) \cdot \alpha) \cdot (z_{ij}^o - (z_{ij}^p - z_{ij}^m) \cdot \alpha) + \\
 & \sum_i^I \sum_k^K (c3_{ik}^o - (c3_{ik}^p - c3_{ik}^m) \cdot \alpha) \cdot (w_{ik}^o - (w_{ik}^p - w_{ik}^m) \cdot \alpha) + \sum_j^J \sum_m^M (c4_{jm}^o - (c4_{jm}^p - c4_{jm}^m) \cdot \alpha) \cdot (v_{jm}^o - (v_{jm}^p - v_{jm}^m) \cdot \alpha) \\
 \text{Subject to;} \\
 & \sum_i^I (x_{li}^p + (x_{li}^m - x_{li}^p) \cdot \alpha) \geq \beta \cdot (Re_l^o - (Re_l^p - Re_l^m) \cdot \alpha) + (1 - \beta) \cdot (Re_l^p + (Re_l^m - Re_l^p) \cdot \alpha) \quad \forall l \in L \\
 & \sum_i^I (x_{li}^o - (x_{li}^p - x_{li}^m) \cdot \alpha) \geq Re_l^o - (Re_l^p - Re_l^m) \cdot \alpha \quad \forall l \in L \\
 & \sum_j^J (z_{ij}^p + (z_{ij}^m - z_{ij}^p) \cdot \alpha) = (1 - ((\gamma^o - (\gamma^p - \gamma^m) \cdot \alpha))) \cdot \sum_i^L (x_{li}^p + (x_{li}^m - x_{li}^p) \cdot \alpha) \quad \forall i \in I \\
 & \sum_j^J (z_{ij}^o - (z_{ij}^p - z_{ij}^m) \cdot \alpha) = (1 - ((\gamma^p + (\gamma^m - \gamma^p) \cdot \alpha))) \cdot \sum_i^L (x_{li}^o - (x_{li}^p - x_{li}^m) \cdot \alpha) \quad \forall i \in I \\
 & \sum_k^K (w_{ik}^p + (w_{ik}^m - w_{ik}^p) \cdot \alpha) = (\gamma^p + (\gamma^m - \gamma^p) \cdot \alpha) \cdot \sum_i^L (x_{li}^p + (x_{li}^m - x_{li}^p) \cdot \alpha) \quad \forall i \in I \\
 & \sum_k^K (w_{ik}^o - (w_{ik}^p - w_{ik}^m) \cdot \alpha) = (\gamma^o - (\gamma^p - \gamma^m) \cdot \alpha) \cdot \sum_i^L (x_{li}^o - (x_{li}^p - x_{li}^m) \cdot \alpha) \quad \forall i \in I \\
 & \sum_m^M (v_{jm}^p + (v_{jm}^m - v_{jm}^p) \cdot \alpha) = \sum_i^I (z_{ij}^p + (z_{ij}^m - z_{ij}^p) \cdot \alpha) \cdot (we^p + (we^m - we^p) \cdot \alpha) \cdot (con^p + (con^m - con^p) \cdot \alpha) \cdot (\alpha_j^p + (\alpha_j^m - \alpha_j^p) \cdot \alpha) \quad \forall j \in J \\
 & \sum_m^M (v_{jm}^o - (v_{jm}^p - v_{jm}^m) \cdot \alpha) = \sum_i^I (z_{ij}^o - (z_{ij}^p - z_{ij}^m) \cdot \alpha) \cdot (we^o - (we^p - we^m) \cdot \alpha) \cdot (con^o - (con^p - con^m) \cdot \alpha) \cdot (\alpha_j^o - (\alpha_j^p - \alpha_j^m) \cdot \alpha) \quad \forall j \in J \\
 & \sum_i^L (x_{li}^p + (x_{li}^m - x_{li}^p) \cdot \alpha) \leq (Cap1_i^p + (Cap1_i^m - Cap1_i^p) \cdot \alpha) \cdot y1_i \quad \forall i \in I \\
 & \sum_i^L (x_{li}^o - (x_{li}^p - x_{li}^m) \cdot \alpha) = \beta \cdot (Cap1_i^p + (Cap1_i^m - Cap1_i^p) \cdot \alpha) \cdot y1_i + (1 - \beta) \cdot (Cap1_i^o - (Cap1_i^p - Cap1_i^m) \cdot \alpha) \cdot y1_i \quad \forall i \in I \\
 & \sum_j^J (z_{ij}^p + (z_{ij}^m - z_{ij}^p) \cdot \alpha) \leq (Cap2_j^p + (Cap2_j^m - Cap2_j^p) \cdot \alpha) \cdot y2_j \quad \forall j \in J \\
 & \sum_j^J (z_{ij}^o - (z_{ij}^p - z_{ij}^m) \cdot \alpha) \leq \beta \cdot (Cap2_j^p + (Cap2_j^m - Cap2_j^p) \cdot \alpha) \cdot y2_j + (1 - \beta) \cdot (Cap2_j^o - (Cap2_j^p - Cap2_j^m) \cdot \alpha) \cdot y2_j \quad \forall j \in J \\
 & \sum_k^K (w_{ik}^p + (w_{ik}^m - w_{ik}^p) \cdot \alpha) \leq (Cap3_k^p + (Cap3_k^m - Cap3_k^p) \cdot \alpha) \quad \forall k \in K \\
 & \sum_k^K (w_{ik}^o - (w_{ik}^p - w_{ik}^m) \cdot \alpha) \leq \beta \cdot (Cap3_k^p + (Cap3_k^m - Cap3_k^p) \cdot \alpha) + (1 - \beta) \cdot (Cap3_k^o - (Cap3_k^p - Cap3_k^m) \cdot \alpha) \quad \forall k \in K \\
 & \sum_j^J (v_{jm}^p + (v_{jm}^m - v_{jm}^p) \cdot \alpha) \leq (Cap4_m^p + (Cap4_m^m - Cap4_m^p) \cdot \alpha) \quad \forall m \in M \\
 & \sum_j^J (v_{jm}^o - (v_{jm}^p - v_{jm}^m) \cdot \alpha) \leq \beta \cdot (Cap4_m^p + (Cap4_m^m - Cap4_m^p) \cdot \alpha) + (1 - \beta) \cdot (Cap4_m^o - (Cap4_m^p - Cap4_m^m) \cdot \alpha) \quad \forall m \in M \\
 & \sum_m^M (v_{jm}^p + (v_{jm}^m - v_{jm}^p) \cdot \alpha) \leq 9 \cdot 10^8 \cdot y2_j \quad \forall j \in J \\
 & \sum_m^M (v_{jm}^o - (v_{jm}^p - v_{jm}^m) \cdot \alpha) \leq 9 \cdot 10^8 \cdot y2_j \quad \forall j \in J \\
 & y1_i, y2_j \in (0,1); x_{li}^o \geq x_{li}^m, x_{li}^m \geq x_{li}^p, x_{li}^p \geq 0; z_{ij}^o \geq z_{ij}^m, z_{ij}^m \geq z_{ij}^p, z_{ij}^p \geq 0 \quad \forall i \in I, \forall j \in J, \forall l \in L \\
 & w_{ik}^o \geq w_{ik}^m, w_{ik}^m \geq w_{ik}^p, w_{ik}^p \geq 0 \quad \forall i \in I, \forall k \in K; v_{jm}^o \geq v_{jm}^m, v_{jm}^m \geq v_{jm}^p, v_{jm}^p \geq 0 \quad \forall j \in J, \forall m \in M
 \end{aligned}$$

- (I) Modelling and optimization component which includes mathematical programming model of the stated FFRLND problem and the proposed parametric method to transform the fuzzy problem into a crisp equivalent form to solve it,
- (II) Data component composed of a database and information communication technology which collects and process the imprecise data as input from the decision maker,
- (III) Decision component which provides the fuzzy solutions of the stated FFRLND problem to the decision maker under various uncertainty levels and different risk attitudes,
- (IV) A user interface for effective and efficient usage and operation of the decision support system by the users.

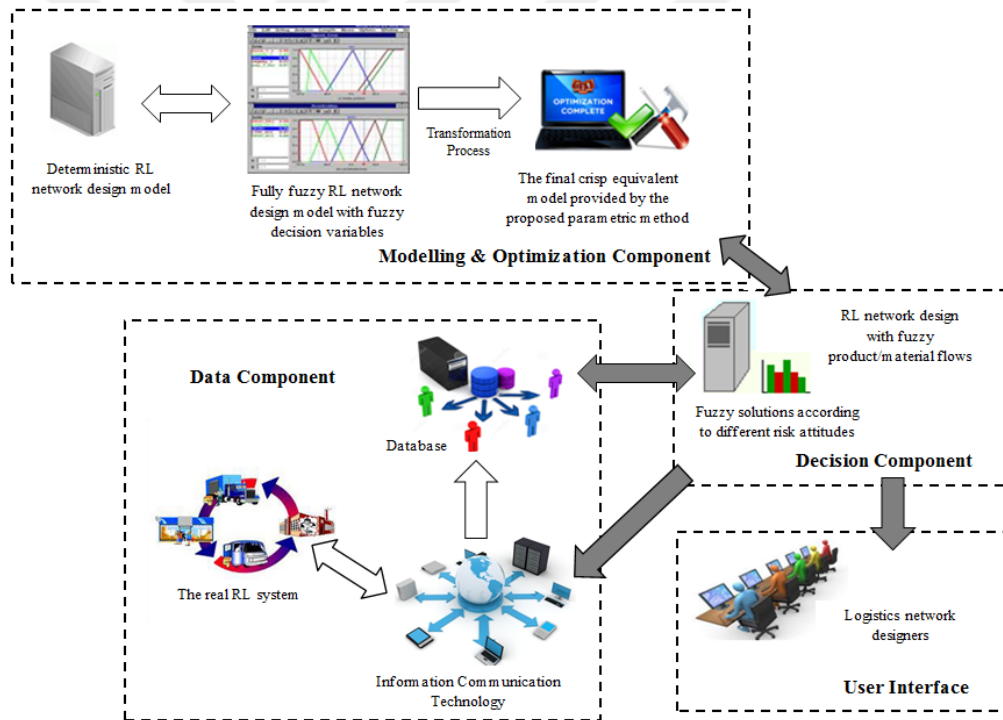


Figure 3.12 An architecture of a decision support system for FFRLND problem

3.6 An Illustrative Case Study

In order to test the performance of the aforementioned methods and show the validity and practicality of the proposed approach, an illustrative example is presented through the FFRLND problem. The configuration of the examined FFRLND problem was demonstrated in Section 3.3 by Figure 3.1. The problem is composed of four

customer zones, three potential collection centers, two potential recycling facilities, two fixed disposal sites and two manufacturing plants. The following fuzzy data are used for presenting the multi-echelon RL network design problem. Moreover, shipping cost (\$) for one kg of recycled material from the recycling facilities to manufacturing plants are (5, 5.5, 6), (4.5, 5, 6.5), (5, 6, 7) and (4, 4.5, 5), respectively. Unit transportation costs, opening/operating costs and capacities of the facilities are also given in Tables 3.15 and 3.16.

Table 3.15 Unit transportation costs (\$) between the different stages

Collection centers	Customer zone-1	Customer zone-2	Customer zone-3	Customer zone-4	Recycling facility-1	Recycling facility-2	Disposal site-1	Disposal site-2
1	(17,19,21)	(15,16,17)	(15,16,17)	(16,18,20)	(8,10,12)	(13,15,17)	(15,17,20)	(13,15,17)
2	(17,19,21)	(12,14,16)	(14,16,18)	(11,13,15)	(15,18,20)	(23,25,27)	(15,18,20)	(11,13,15)
3	(22,25,27)	(18,20,22)	(20,21,23)	(20,22,24)	(28,30,32)	(30,32,35)	(18,20,22)	(23,25,27)

In addition, disposal capacities for the scrap products are determined as (100, 200, 300) and (150, 200, 250). Furthermore, warehousing capacities of each manufacturing plant for recycled materials are taken as (5000, 5500, 6000) and (6000, 6500, 7000), respectively. The other fuzzy parameters such as recovery rate for each recycling facility, disposal fractions etc. are presented in Table 3.17.

Table 3.16 Opening/operating costs (\$) and capacities (units) of collection and recycling facilities

Collection center-1	Collection center-2	Collection center-3	Recycling facility-1	Recycling facility-2
(80000,100000,120000)	(130000,150000,170000)	(170000,200000,210000)	(250000,300000,350000)	(350000,400000,430000)
(550,650,800)	(550,700,850)	(600,800,1000)	(800,900,950)	(700,750,800)

Table 3.17 Other information on the case study

Recycling rate	Disposal fraction	Product weight (kg.)	Material Contribution
(50%, 60%, 70%)	(5%, 10%, 15%)	(8,10,12)	(60%, 70%, 80%)
(70%, 80%, 90%)	-	-	-

Finally, amounts of returned products (in units) from the customer zones are taken as (250, 300, 350), (300, 350, 400), (250, 300, 350) and (300, 350, 400), respectively. LINGO 15.0 optimization software is used to solve the crisp versions of the fully fuzzy mathematical programs for the stated RL network design problem on an Intel Core i7 2 GHz PC by making use of the above data.

3.6.1 Comparison of the Computational Results

First of all, the problem is solved under fully deterministic environment where all of the above fuzzy parameters are assumed to have most likely values (or core values) of the triangular fuzzy numbers. For this crisp case, the obtained RL configuration is depicted in Figure 3.13. Afterwards, the comparisons of the yielded solutions for the stated FFRLND problem are summarized in Table 3.18 by applying the different fuzzy solution methods from the existing literature.

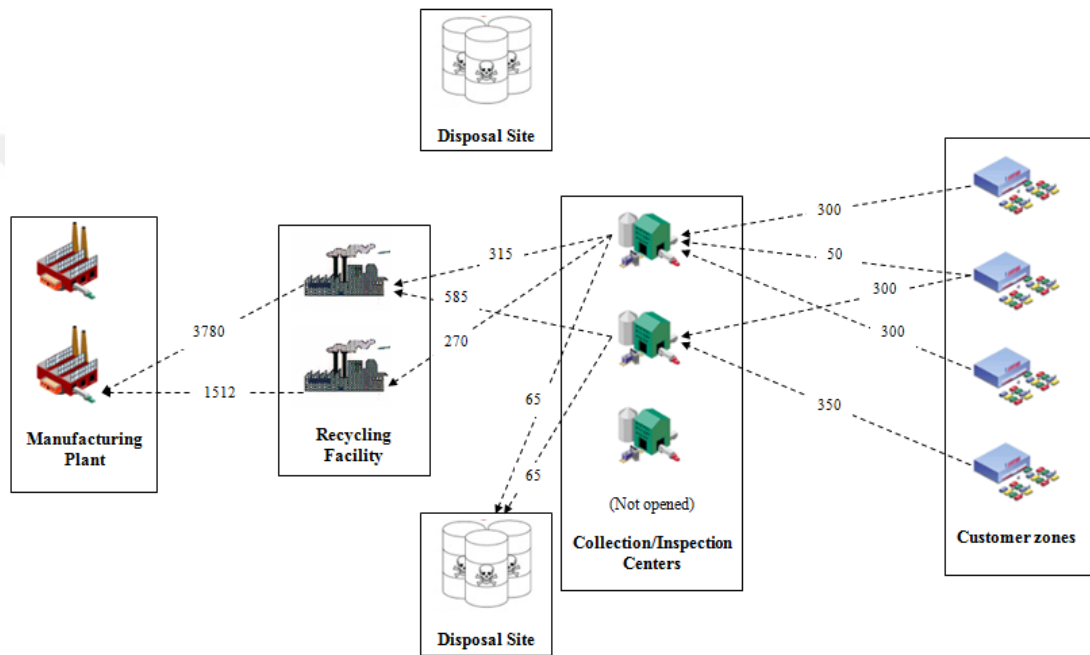


Figure 3.13 Optimal product/material flows in the RL network under fully deterministic environment

According to Table 3.18, Jayalakshmi and Pandian's method (2012) provided same outcomes with the method of Kumar et al. (2010) and (2011) as an expected result.

Table 3.18 Summary of the results obtained from the different fuzzy solution methods

FFLP results	Crisp	Allahviranloo et al.'s (2008) method	Kumar et al.'s (2010 & 2011) method	Jayalakshmi & Pandian (2012)			Proposed approach ($\alpha=0$ and $\beta=0$)
				Lower level	Middle level	Upper level	
Total number of variables	33	92	137	28	33	28	96
Total number of binary variables	5	5	5	5	5	5	5
Total number of constraints	24	83	155	53	24	53	133
Total number of iterations	113	160	93	0	99	11	18
Objective value	\$1015304	\$1010165 (841049.2, 1000493, 1223463)	\$1016271 (847725.6, 1015304, 1186752)	\$847725.6	\$1015304	\$1186752	\$2034478 (847725.6, 1015304, 1186752)
Fuzzy objective	-			(847725.6, 1015304, 1186752)			

Although the crisp equivalent form of the FFRLND problem obtained from the method of Kumar et al. (2010) and (2011) have more variables and constraints, solving the decomposed models separately in the method of Jayalakshmi and Pandian (2012) may be more difficult for the analyst or decision maker(s). Because, all of the results obtained from one model are used as constraints' bounds into another model. But, it is obvious that the solution of a large scaled FFLP problems by the method of Kumar et al. (2010) and (2011) will need more computational effort since including large amounts of variables and constraints. The corresponding optimal RL networks provided by these methods are presented in Figures 3.14 and 3.15, respectively.

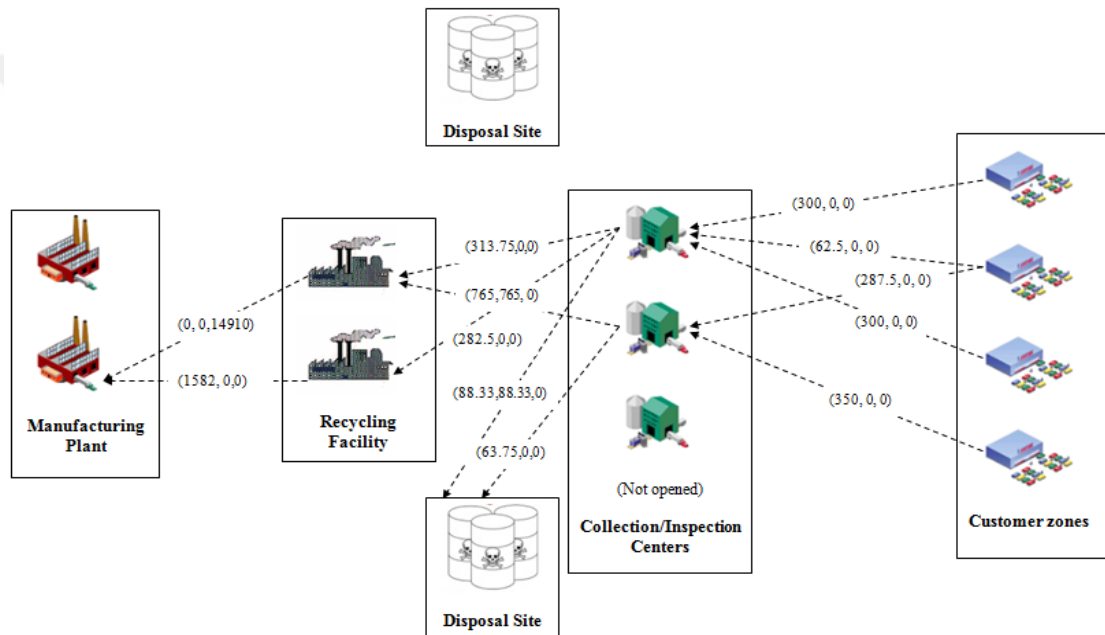


Figure 3.14 Fuzzy efficient product flows obtained from the method of Allahviranloo et al. (2008)

It should also be emphasized here that nearby solutions can be provided by using less variables and constraints with the help of Allahviranloo et al.'s method (2008). However, this method yields only the approximate solution instead of an exact one. Because, it depends on the usage of an approximation to the nearest symmetric triangular fuzzy numbers for all of the uncertain parameters and decision variables. The results of the stated FFRLND problem for different risk attitudes or β values are presented in Table 3.19. In the case of smaller values of β , the objective function value will decrease. However, the risk for unavailable capacity of sources (collection centers, disposal sites, recycling and manufacturing facilities) and unsatisfactory demand of

customers (collection requests for the returned products) will increase. Thus, the transportation quantities will take more imprecise values when the risk sensitivity of the decision maker is low (or risk-seeker). This statement is also supported by the Figures 3.16 and 3.17.

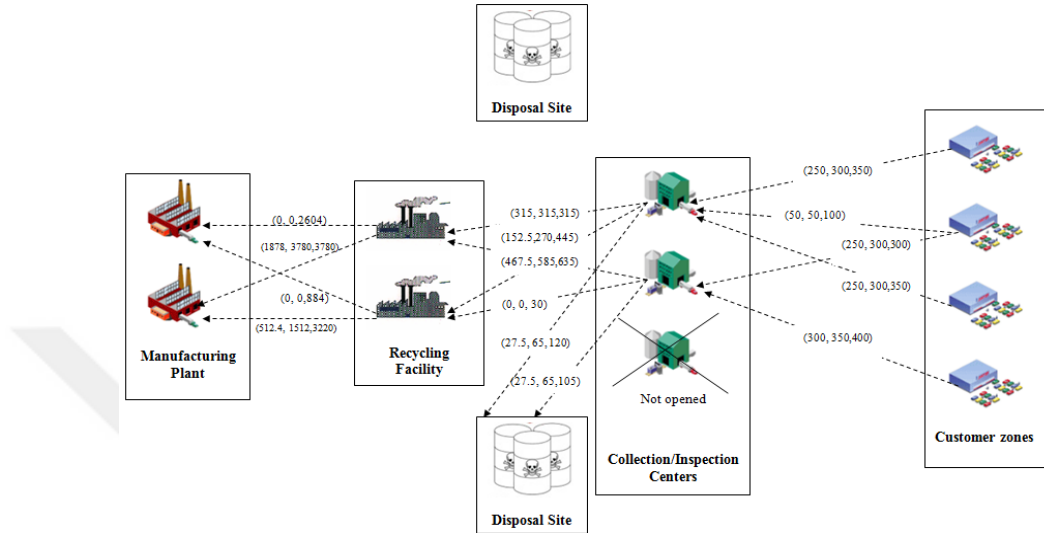


Figure 3.15 Fuzzy efficient product flows obtained from the methods of Kumar et al. (2010) and (2011), Jayalakshmi and Pandian (2012) and proposed method for a risk-seeker ($\beta=0$)

As it is seen from Figures 3.16 and 3.17 that change of the membership function forms for the customer zone-2 and collection center-1 are presented with respect to the usage of different risk sensitivity degrees.

Table 3.19 Fuzzy efficient solutions by the proposed method considering different risk attitudes

Sources/ Destinations	$\beta = 1$ (Risk-averse)	$\beta = 0.70$ (Partially risk-averse)	$\beta = 0.5$ (Risk-neutral)	$\beta = 0.1$ (Partially risk-seeker)	$\beta = 0$ (Risk-seeker)
CZ1-CC1	(200, 200, 200)	(320, 320, 350)	(300, 300, 350)	(260, 300, 350)	(250, 300, 350)
CZ2-CC1	(0, 0, 0)	(0, 0, 15)	(0, 0, 25)	(30, 50, 75)	(50, 50, 100)
CZ2-CC2	(150, 150, 150)	(180, 180, 195)	(200, 200, 225)	(0, 0, 0)	(250, 300, 300)
CZ2-CC3	(250, 250, 250)	(190, 190, 190)	(150, 150, 150)	(280, 300, 325)	(0, 0, 0)
CZ3-CC1	(350, 350, 350)	(230, 230, 260)	(250, 250, 300)	(260, 300, 350)	(250, 300, 350)
CZ3-CC3	(0, 0, 0)	(90, 90, 90)	(50, 50, 50)	(0, 0, 0)	(0, 0, 0)
CZ4-CC2	(400, 400, 400)	(370, 370, 400)	(350, 350, 400)	(0, 0, 0)	(300, 350, 400)
CZ4-CC3	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(310, 350, 400)	(0, 0, 0)
CC1-RF1	(332.5, 332.5, 332.5)	(332.5, 332.5, 332.5)	(332.5, 332.5, 332.5)	(467.5, 567.5, 602.5)	(315, 315, 315)
CC1-RF2	(135, 162.5, 190)	(135, 162.5, 261.25)	(135, 162.5, 308.75)	(0, 17.5, 133.75)	(152.5, 270, 445)
CC2-RF1	(467.5, 467.5, 467.5)	(467.5, 495, 512.5)	(467.5, 495, 542.5)	(0, 0, 0)	(467.5, 585, 635)
CC2-RF2	(0, 27.5, 55)	(0, 0, 52.75)	(0, 0, 51.25)	(0, 0, 0)	(0, 0, 30)
CC3-RF1	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(332.5, 332.5, 332.5)	(0, 0, 0)
CC3-RF2	(340, 360, 380)	(238, 252, 266)	(170, 180, 190)	(169, 252.5, 356.25)	(0, 0, 0)
CC1-DS1	(0, 0, 15)	(0, 0, 3)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
CC1-DS2	(27.5, 55, 67.5)	(27.5, 55, 90.75)	(27.5, 55, 101.25)	(27.5, 65, 116.25)	(27.5, 65, 120)
CC2-DS2	(27.5, 55, 82.5)	(27.5, 55, 89.25)	(27.5, 55, 93.75)	(0, 0, 0)	(27.5, 65, 105)
CC3-DS1	(20, 40, 60)	(14, 28, 42)	(10, 20, 30)	(29.5, 65, 108.75)	(0, 0, 0)
RF1-MP1	(1544, 2984, 5000)	(1541.6, 3097.1, 5300)	(1540, 3095.5, 5500)	(1536.8, 3396.8, 5900)	(0, 0, 2604)
RF1-MP2	(376, 376, 376)	(378.4, 378.4, 378.4)	(380, 380, 380)	(383.2, 383.2, 383.2)	(1878, 3780, 3780)
RF2-MP1	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 884)
RF2-MP2	(1596, 3080, 5400)	(1253.28, 2321.2, 5011.2)	(1024.8, 1918, 4752)	(567.84, 1512, 4233.6)	(512.4, 1512, 3220)
Fuzzy Objective	(1041094, 1236327, 1402904)	(1034243, 1226988, 1399992)	(1029677, 1221029, 1398065)	(900698.3, 1078670, 1237365)	(847725.6, 1015304, 1186752)

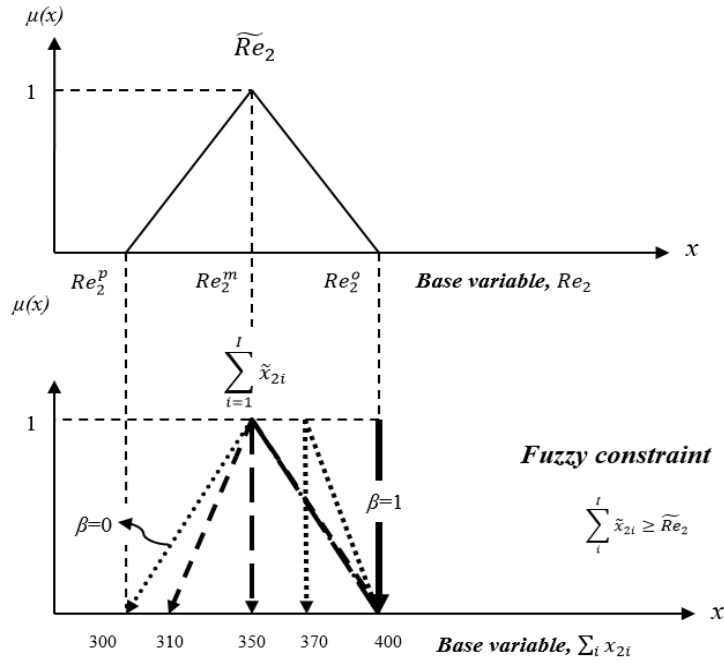


Figure 3.16 Membership functions of outgoing flows from customer zone-2 with different β values

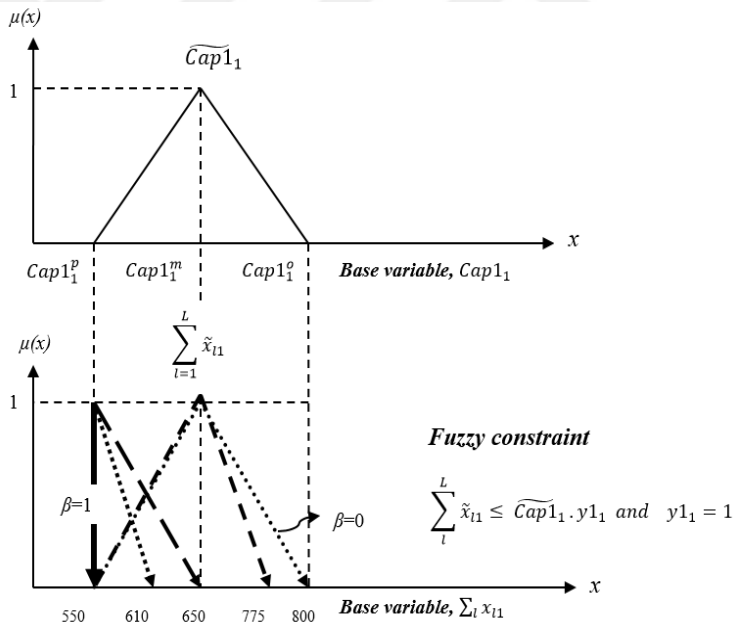


Figure 3.17 Membership functions for incoming flows to collection center-1 with different β values

Furthermore, optimal product flows and the regarding RL network obtained by the proposed method for a risk-averse decision maker is also depicted in Figure 3.18. The membership function of the fuzzy objective which is yielded by applying the different methods is given in Figure 3.19. It is clearly seen from Figure 3.19 that the method of Kumar et al. (2010) and (2011) and Jayalakshmi and Pandian (2012) outperformed

than the method of Allahviranloo et al. (2008) since they provide better fuzzy objective value. In detail, smaller left and right widths are provided for the fuzzy objective value by these methods.

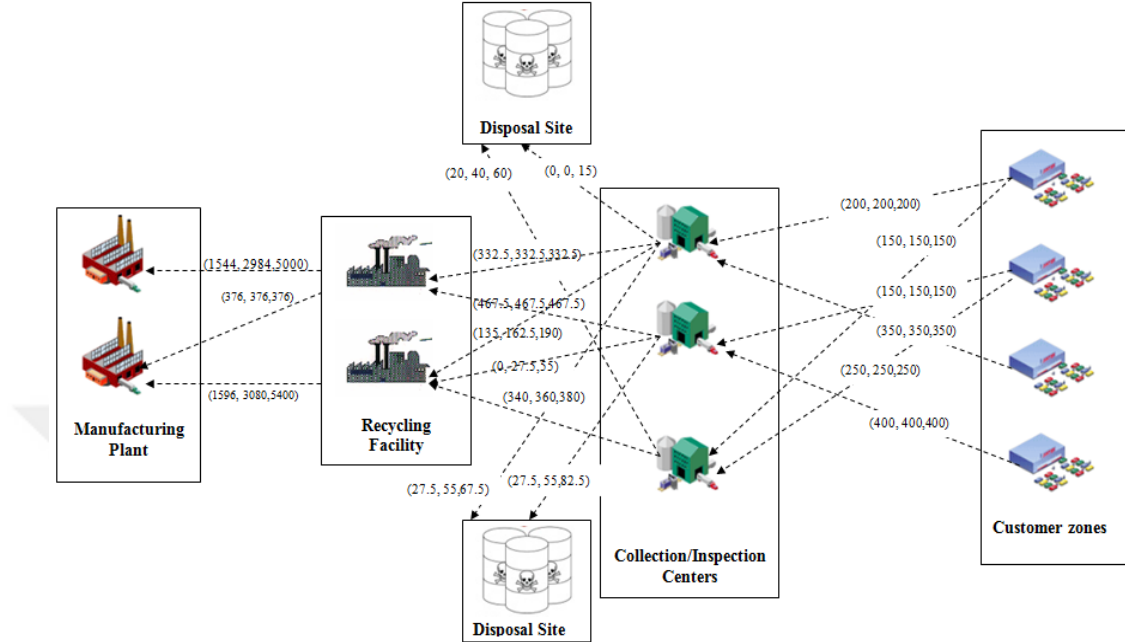


Figure 3.18 Fuzzy optimal product flows by proposed approach for a risk-averse decision maker ($\beta=1$)

However, the method of Allahviranloo et al. (2008) has smaller core value (\$1000493) for the fuzzy objective. On the other hand, this method tends to find crisp solutions as it can be seen from the Figure 3.14. Nonetheless, it is possible to acquire very close results by using the method of Allahviranloo et al. (2008) to the fuzzy solutions obtained from the methods of Kumar et al. (2010) and (2011) and Jayalakshmi and Pandian (2012) with the usage of less variables and constraints.

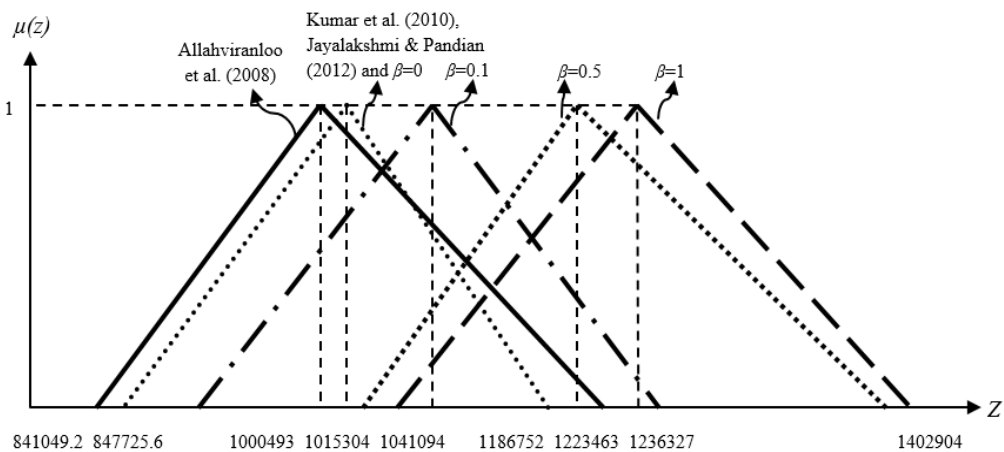


Figure 3.19 Membership functions of fuzzy objective value by different solution methodologies

As it can be seen from Figure 3.19, total cost of the RL system will be greater than the existing methods' results for the risk-averse decision maker ($\beta=1$) as expected. Moreover, the proposed method tends to provide crisp solutions for the risk-averse decision maker(s). In other words, necessarily precise solutions can be yielded by the proposed method in case of risk aversion. In contrast, more imprecise solutions which have great deals of uncertainty will be produced for the risk-seekers as in the existing methods' results.

3.7 Chapter Summary

In this chapter, a detailed review and analysis of the solution procedures which are developed for solving fully fuzzy linear programming problems with fuzzy decision variables have been presented. Furthermore, a new parametric method which incorporates the decision maker(s)'s attitude toward risk is proposed. In fact, risk-free and/or risky solutions can be provided by utilizing the proposed method according to the risk sensitivity degree of decision maker(s). Moreover, since most of the methods in the literature were usually applied to very small scaled and trivial problems, application of three relatively new methods, i.e. Allahviranloo et al.'s approach (2008), Kumar et al.'s approach (2010) and (2011) and bound and decomposition method of Jayalakshmi and Pandian (2012), to a fully fuzzy RL network design problem with fuzzy decision variables are presented first time in the literature. This research also presents how to formulate closed-form mathematical representations of the employed methods that can be easily handled by algebraic modelling languages for optimization with commercial packages like LINGO etc.

The optimization results show that Kumar et al.'s method (2010) and (2011), Jayalakshmi and Pandian's (2012) method and Allahviranloo et al.'s (2008) approximate method provided similar results when compared to the proposed method with risk-seeking. The computational results also showed that more realizable, reliable and information efficient solutions can be achieved for risk-averse decision maker(s) by using the proposed method. In addition, the decision maker(s) will be supported with yielding fuzzy efficient solutions under different uncertainty levels (α -cut) and risk attitudes. It should also be noted here that, in all of the studied methods, the

number of decision variables and constraints will increase considerably after transforming the fuzzy models into crisp equivalents. The number of decision variables is increased three to four times, similarly the number of constraints is increased four to five times. Allahviranloo et al.'s (2008) approximate method generates smallest increases in model size with compared to the other two methods.

In this chapter, a small sized and less complicated RL network design problem is studied. If a moderate sized network with multiple objectives, time periods, products, closed-loops etc. is considered, the model size will tremendously increase and the applicability of these fuzzy solution methods will be questionable. Therefore, there is an urgent need to develop efficient direct solution methods which do not require fuzzy to crisp conversion procedures for solving practical fully fuzzy mathematical programs with fuzzy decisions variables. It seems that a fuzzy optimization problem needs a fuzzy solution algorithm with an acceptable definition of fuzzy optimal solution.

CHAPTER FOUR
A HYBRID SCENARIO BASED STOCHASTIC & POSSIBILISTIC
PROGRAMMING APPROACH FOR A CLOSED-LOOP SUPPLY CHAIN
NETWORK DESIGN WITH RISK CONSIDERATION

4.1 Chapter Introduction

Recently, there is a great deal of interest in risk management issues by both researchers and practitioners in the scope of supply chain (SC) management. It is emphasized by You et al. (2009) that in addition to cost reduction and profit maximization, managing the risks along the SCs has drawn significant attention due to the competition in the global marketplace. Due to the global competition, technological change and continual search for competitive advantage, risk management in SCs has been an attractive research topic. In SC risk management, coordination and collaboration of processes and activities across functions within a network of organizations are generally handled (Wu & Olson, 2013). According to Wang and Hsu (2010), the uncertainty embedded in Reverse Logistics (RL) and Closed-Loop Supply Chains (CLSC) has been a challenge for green supply chain concept. Because, the uncertain factors of the reverse flows are more complex than the forward part of the supply chain. Apart from the uncertain demand, the values of recovery rate and disposal rate pose difficulties in estimation and constitute the major factors of the CLSC management. Indeed, inaccurate forecasting of these parameters causes increases in various types of financial risks and also the risks related to the collection and recovery amounts. Thus, risk management has an important role in controlling the uncertainty level in supply chain optimization problems. It is highlighted by Azaron et al. (2008) that minimization of the risk reflected by the variance of the total cost which is named as financial risk, has not been considered in the existing SC network design models sufficiently. Babazadeh et al. (2012) also supported this viewpoint by denoting the lack of SC, RL and CLSC network design models which are able to measure and control the risks resulting from the dynamic and uncertain nature of the problem. Additionally, all of the quantitative risk management models in these network design problems focus only on the financial risk issues as a result of the considered objective function (minimize total cost and/or maximize

overall profit). On the other hand, strict legal obligations and the environmental awareness put pressure on enterprises for collection and recovery of used scrap products as much as possible. Therefore, the risk of non-collecting the end-of-life products up to the pre-determined target value emerges as an important issue in CLSC management and RL environments. For these reasons, the risk of end-of-life product collection should also be modeled quantitatively besides the financial risks. In this context, collection risk can be defined as the “*probability of not collecting the used products up to a certain level or target defined by the environmental laws*”.

Before applying different risk management models to a SC, CLSC or RL network design models, uncertainties related to the studied problem should be taken into account effectively as risks mostly take root from the uncertainties. In other words, main sources of the risks are related to uncertainties in the stated problem. However, most of the real-life applications involve different uncertainty types (randomness, fuzziness and dynamism) altogether. On the other hand, the majority of the papers in the literature deal with these uncertainty categories separately. In fact, these uncertainty types should be taken into account simultaneously. Therefore, this chapter presents a hybrid multi-scenario based stochastic and possibilistic programming approach to a lead/acid battery CLSC network design problem where stochastic parameters have randomness in nature and possibilistic parameters are represented by triangular fuzzy numbers. Then, different risk measures such as “*variability index*”, “*downside risk*” and “*conditional value at risk*” are integrated within the proposed mixed-integer linear programming model.

Briefly, the main purpose of this chapter is to develop a new multi-objective CLSC network design model for a lead/acid battery industry considering risk measures both financial and collection objectives simultaneously. Another important aim is to handle different uncertainty types such as randomness, fuzziness etc. altogether in the same problem since it can better reflect the real-life cases. Moreover, utilized target/threshold values should be taken as fuzzy data while formulating the downside risk metric because of the lack of some information and some sort of ambiguity. In detail, target/threshold values are considered as fuzzy and described by their own possibility distribution for the downside risk measure. To the best of our knowledge,

this chapter constitutes the first research in the literature which considers the uncertainty embedded into the mentioned targets. At the end of this chapter, all of the utilized risk management models for the stated CLSC network design problem under uncertainty are compared.

The rest of the chapter is organized as follows. In Section 4.2, the relevant literature on RL and CLSC network design problem under uncertainty and the risk management models for SC, RL and CLSC planning problems are given. In Section 4.3, the details of the examined problem with model formulation, assumptions and model parameters are described. Transformation of the hybrid model into the equivalent auxiliary crisp and stochastic form is also given in the same section. In Section 4.4, application of the proposed model to an illustrative example inspired by a lead/acid battery case in Turkey is discussed. Adaption and comparison of the previously mentioned risk management metrics into the proposed hybrid model is given in Section 4.5. In Section 4.6, chapter conclusions and suggestions for future research directions are presented.

4.2 Literature Review on Supply Chain, Closed-Loop Supply Chain and Reverse Logistics Network Design under Uncertainty and Risk

Uncertainty is one of the main attentions in CLSC management due to the demand, disposal and recovery rates which are the three important factors contributed to the uncertainty (Wang & Hsu, 2010). In other words, uncertainty in timing, quality and quantity of product returns are important aspects of RL and CLSC network design problems. However, development of dynamic, probabilistic and stochastic SC and production-distribution planning models is still investigated by relatively few researchers (Fahimnia et al., 2013). In addition, they emphasized the development of these types of models as the future research trends. Wang and Hsu (2010) also highlighted that appropriate models which aim to handle the uncertainty in CLSCs is still lacking. As mentioned by Ilgin and Gupta (2010), this uncertainty issue can be handled by using robust optimization techniques in stochastic RL network design models. Additionally, fuzzy mathematical programming can also be used since the deterministic models assumed certainty in all aspects of the problem although some of the parameters cannot be precisely set like capacities and target for objective function

achievement (Bilgen, 2010). The articles handling uncertainty issue and discussing related methodologies can be summarized as follows. Salema et al. (2007) reformulated the generic RL network design model while taking into account the production/storage capacities of opened facilities, multiple products and uncertainty related to the amounts of customers' demand and product returns by employing multiple-scenario based stochastic programming approach. A multi-echelon CLSC inventory control model is proposed by Chung et al. (2008) in order to obtain optimal inventory policy for maximizing the joint profits of the supplier, manufacturer, and third-party recycle dealer or retailer. Pishvaei et al. (2009) developed a stochastic programming model for a CLSC network design by using scenario-based stochastic programming approach. In that paper, demands, quantity and the quality of product returns and the variable costs were considered as uncertain parameters. A two-stage stochastic programming model was proposed by Kara and Onut (2010) for single product, two-echelon capacitated RL network design in waste paper recycling industry in order to maximize the revenue. Demand and amounts of collected products were assumed to be uncertain and fitted to the normal distribution while generating alternative scenarios. El-Sayed et al. (2010) developed a multi-period, multi-echelon and multi-stage stochastic program for an integrated forward-reverse logistics network design while assuming the demands of customer zones to be stochastic. Lee et al. (2010) also proposed a two-stage stochastic programming model for sustainable logistics network design. Demands of forward products and the supply of returned products are assumed to be stochastic parameters which have known probability distributions. Uncertain demands, returns, delivery times, costs and capacities were taken into account by using possibilistic programming approach by Pishvaei and Torabi (2010) for a CLSC network design problem which integrates strategic and tactical planning decisions. Because of some disadvantages of the stochastic programming such as difficulty related to availability of historical data and complex modeling, uncertain demand and purchasing cost in strategic agile CLSC network design problem of perishable goods was handled via interval robust optimization technique by Hasani et al. (2012). Uncertainties in demand and yield rate are modeled by Qiang et al. (2013) for a CLSC network with decentralized decision makers that consist of raw material suppliers, retailers and manufacturers. Subulan et al. (2012)

developed a fuzzy mixed integer programming model with non-linear constraints for medium-term planning in a CLSC with remanufacturing option. In their proposed model, storage capacities, demands of retailers and wholesalers, return rates, acceptance ratios, weekly available production/remanufacturing times, transportation upper bounds and objective function value are considered as fuzzy. A fuzzy rule-based system for performance evaluation of a CLSC network was also developed by Olugu and Wong (2012) in automotive industry. Pishvaei and Razmi (2012) developed a multi-objective possibilistic mixed-integer programming model for an environmental supply chain network design. They used possibilistic programming approach for handling the imprecise parameters such as lower cost items, demands, return quantities and the facilities' capacities.

Apart from the existing literature, this chapter presents a hybrid of stochastic and possibilistic mixed-integer programming model for a CLSC network design problem since the real-life applications involve different types of uncertainties simultaneously. On the other hand, greater amount of the articles in the literature deal with these uncertainty categories separately as mentioned before. In the proposed model, multi-scenario based stochastic programming approach and possibilistic programming are utilized jointly. Demands, return rates and quality of the returned products are considered as stochastic parameters since they have randomness in nature. Furthermore, because they may have epistemic uncertainty (unavailability or incompleteness of the historical data, insufficient data etc.) all of the cost parameters, recycling rates, maximum number of opened facilities, maximum allowable distances for distribution and collection coverages are considered as possibilistic parameters and described by possibility distributions.

In the scope of risk management in SC, CLSC and RL network design, most commonly used risk management metrics are explained by You et al. (2009) as follows:

- Managing the variance,
- Managing the variability index,
- Managing the probabilistic financial risk and finally
- Managing the downside risk.

Different from the above risk measures, Conditional Value at Risk (CVaR) criterion which was proposed by Rockafellar and Uryasev (2000) was used by Babazadeh et al. (2012) in order to measure the investment risk and control the risk level of their CLSC planning model. In this chapter, variance management model is not applied since the objective function includes non-linear terms which make large scaled problems very difficult to be solved optimally. Therefore, as an alternative to variance measure, variability index model is used in order to obtain low variance in a more effective manner. In addition, it is also emphasized by You et al. (2009) that variance management model is not an effective tool in reducing the high cost risk, only lead to less variance, or in other words, reducing the probability of lower cost. A similar circumstance is also valid for the probabilistic financial risk measure. As mentioned by Guillen et al. (2005) that downside risk can be used instead of probabilistic financial risk because of avoiding the use of binary variables for each scenario which will increase the size of the model. This makes the problem's size very large as the number of scenarios increases. As a result, downside risk is used in this chapter instead of probabilistic financial risk metric. As reported by You et al. (2009) and Guillen et al. (2005), downside risk management model is the most effective tool or the best choice among the others since its computational efficiency. Available literature that uses the above risk measures in SC, CLSC and RL network design concept can be summarized as in Table 4.1.

Table 4.1 Risk management models for SC, CLSC and RL network design

Article	Prob. Type	Risk Measures					CVaR
		Variance	Variability Index	Probabilistic Financial Risk	Downside Risk (Deterministic)	Downside Risk (Fuzzy)	
Shah (2004)	SC				✓		
Barbaro et al. (2004)	CP			✓	✓		
Guillen et al. (2005)	SC			✓	✓		
Azaron et al. (2008)	SC	✓		✓			
You et al. (2009)	SC	✓	✓	✓	✓		
El-Sayed et al. (2010)	CLSC						
Gebreslassie et al. (2012)	SC				✓		✓
Nickel et al. (2012)	SC				✓		
Babazadeh et al. (2012)	CLSC						✓
Ramezani et al. (2013)	CLSC			✓			
Our research	CLSC		✓		✓	✓	✓

CP: Capacity planning

In this chapter, following contributions are made by developing a new case-oriented mathematical programming approach for a lead/acid battery closed-loop supply chain network design problem under risk and uncertainty:

- A novel hybrid scenario based stochastic and possibilistic programming model is proposed for Turkish lead/acid battery industry while taking into account different uncertainty types such as randomness, fuzziness etc. simultaneously.
- In the proposed model, real-life decision making situations in the lead/acid battery sector related to the purchasing and/or selling of end-of-life batteries to the scrap dealers are also considered. Moreover, decision related to the types of the facilities such as distribution, collection or hybrid that will be opened is as important as where they will be located in the examined sector. Therefore, in addition to determine the facility locations, facility type is also handled in the developed model for the candidate locations.
- In contrast to the existing risk management models in the literature, this chapter does not focus only the financial risk issues but also the risk of non-collecting the end-of-life products up to a pre-determined target value. In other words, collection risks of used batteries are also considered besides the financial risks in an integrated manner.
- In most of the risk management metrics, target values of the objectives related to the risk issues were determined as certain parameters by the decision maker(s). However, specification of this value in a definite way is a challenging task since including some sort of ambiguity. For this reason, this chapter deals with imprecise target values which are represented by triangular fuzzy numbers under uncertain environments.

4.3 Problem Definition and Hybrid Stochastic & Possibilistic Model Formulation

Lead/acid battery industry requires an optimal design for the CLSC network. In this research, not only “*opening of regional wholesalers for forward flows of newly produced batteries*” and “*the setting up of the collection centers for reverse flows*”, but also “*a hybrid facility which undertake the transfer of both forward and returned batteries*” are taken into account as in the model developed by Lee et al. (2010). In the forward supply chain, in addition to provide some materials from the recycling way,

the main components of a lead/acid battery are purchased from different vendors for new battery production. Once the battery is produced in different new battery manufacturers it has to be distributed via regional wholesalers or hybrid facilities to the dealers or retailers. In the reverse supply chain, the end user leaves the spent battery at the retailer where it is replaced by a new one at the end of battery use. Then, the collected spent batteries are transported to the licensed recycling facilities through collection centers or hybrid facilities. Used batteries are controlled in terms of quality specifications for recycling process. The useless batteries are disposed of and the appropriate batteries for recycling are shipped to the licensed recycling facilities which are secondary lead smelters and plastic recyclers. In accordance with the need for spent battery, additional used batteries can be purchased from the scrap dealers or conversely sales to the excessive batteries to scrap dealers can be performed. The discussed CLSC network configuration for a lead/acid battery industry can be displayed as in the following Figure 4.1.

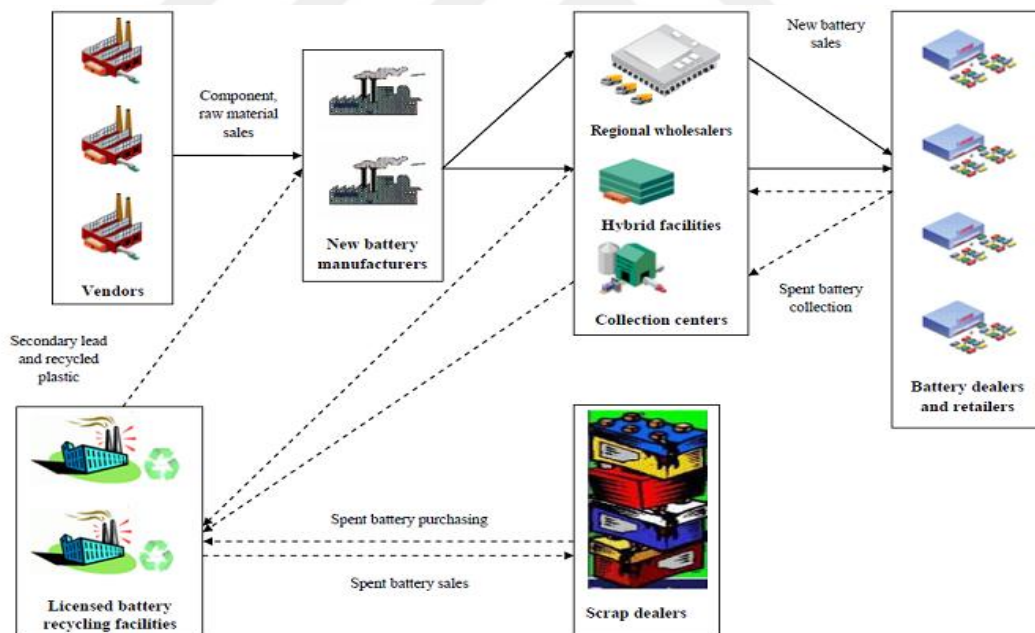


Figure 4.1 Closed-loop supply chain network representation for lead/acid battery recovery

The model assumptions for developing the mixed-integer linear program (MILP) can be stated as follows:

- There are two different options for the new battery manufacturers to supply components such as lead, plastic etc. One is purchasing them from different

suppliers; and the other one is acquiring them by recycling from the licensed recycling facilities.

- Shortages and inventory holding are not allowed and cost parameters at all stages of the CLSC network do not change. Transportation lead times between the stages are not taken into account because of the single period consideration.
- The dealers' or retailers' demand forecasts, return rate for the used batteries and the disposal fraction are not exactly known and considered as stochastic parameters. Quantity of returned batteries from a given dealer or retailer is the fraction of the total demand of that dealer or retailer.
- Any collection center or hybrid facility can purchase additional scrap batteries from the scrap dealers for recycling if it is needed. Furthermore, this collection center or hybrid facility can also sell a certain amount of their collected scrap batteries to the scrap dealers if it has a cost advantage. However, purchasing and selling operation for the same type of scrap battery cannot be performed simultaneously and at most one alternative can be done. On the other hand, these operations, i.e., purchases and sales, can be performed at the same time for different types of scrap batteries by the collection center or hybrid facility.
- It is assumed that physical locations of scrap dealers have no impact on the CLSC network design and they have an infinite capacity and budget for used battery sales or purchasing.

4.3.1 A Hybrid Scenario Based Stochastic and Possibilistic MILP Formulation

The uncertainty in data can be categorized into two groups: (i) randomness and (ii) epistemic uncertainty. In general, stochastic programming and possibilistic approaches were used for handling these types of uncertainties (Mula et al., 2006; Pishvae & Razmi, 2012). The main sources of epistemic uncertainty are the unavailability or incompleteness of the historical data (insufficient data). Epistemic uncertainty deals with the ill-known parameters which have their own possibility distribution. Thus, using probability distributions as in the stochastic optimization becomes impossible. In this situation, possibility distributions should be forecasted based on the decision makers' experiences or knowledge (Pishvae & Razmi, 2012). In this chapter, all of the cost parameters as well as selling prices of different kinds of lead/acid batteries,

maximum number of opened collection centers and hybrid facilities, recycling rates, maximum allowable distances for new battery distribution and used battery collection are considered as ill-known parameters and represented by triangular fuzzy numbers which are described by possibility distributions. However, other uncertainty factors such as “*demands of the dealers*”, “*return fractions for the end-of-life batteries*” and “*the disposal rates*” which constitute the dynamics of RL and CLSC management are considered as stochastic parameters. Therefore, the proposed hybrid mathematical model takes into account the deterministic, stochastic and possibilistic parameters in an integrated manner. For better understanding of the proposed hybrid multi-scenario based stochastic and possibilistic model, the compact form of the MILP formulation can be shown as follows:

$$OF1 = \text{Min } \tilde{f} \cdot y + \sum_{s \in S} \pi_s \cdot \beta_s \cdot \tilde{\alpha} \cdot x_s \quad (4.1)$$

$$OF2 = \text{Max } \sum_{s \in S} \pi_s \cdot c_s \cdot y_s'' \quad (4.2)$$

Subject to:

$$a \cdot x_s \leq b \quad (4.3)$$

$$c_s \cdot x_s = d_s \quad (4.4)$$

$$y \leq \tilde{e} \quad (4.5)$$

$$g \cdot y_s'' = \tilde{h} \quad (4.6)$$

$$x_s = \tilde{k} \quad (4.7)$$

In the above formulation, $\tilde{f}$ and $\tilde{\alpha}$ correspond to possibilistic cost parameters. $\tilde{e}$, $\tilde{h}$, $\tilde{k}$ and d_s represent possibilistic and stochastic right hand sides, respectively. b and g correspond to deterministic coefficients and y displays binary variables independent from the scenarios. On the other hand, y_s'' are also binary variables for each scenario s . The continuous variables x_s correspond to the flows between the CLSC stages for each scenario.

Because of satisfying the demand and return requirements of battery dealers in each scenario and avoiding the infeasibility problem, the locations and numbers of facilities cannot be changed (Pishvae et al., 2009). Therefore, scenario index s should not be added to the facility opening decisions such as w_j , c_j and h_j . According to these

explanations, a multi-objective, multi-echelon, multi-product hybrid stochastic and possibilistic CLSC network design model can be given through the following equations by using the indices, parameters and decision variables which are defined as in Table 4.2. The first objective function of the hybrid MILP model is to minimize the total expected CLSC cost which involves imprecise cost parameters.

$$\begin{aligned}
E[Total\ CLSC\ Cost] = & \sum_{j \in J} \widetilde{f1}_j \cdot w_j + \sum_{j \in J} \widetilde{f2}_j \cdot c_j + \sum_{j \in J} \widetilde{f3}_j \cdot h_j + \sum_{l \in L} \widetilde{f4}_l \cdot r_l + \\
& \sum_{b \in B} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot Q_{bis} \cdot \overline{PRC}_b + \sum_{b \in B} \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{s \in S} \pi_s \cdot x_{bijks} \cdot \widetilde{TC}_b \cdot (d1_{ij} + d2_{jk}) + \\
& \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot x1_{bkjls} \cdot \widetilde{TC1}_b \cdot (d2_{jk} + d3_{jl}) + \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot q_{bjls} \cdot \widetilde{TC1}_b \cdot d3_{jl} + \\
& \sum_{c \in C} \sum_{l \in L} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot x2_{clis} \cdot \widetilde{TC}_c \cdot d4_{li} + \sum_{c \in C} \sum_{v \in V} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot QP_{cvis} \cdot \overline{PUC}_{cvi} + \\
& \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot q_{bjls} \cdot \widetilde{PC}_{bj} + \sum_{b \in B} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot RE_{bls} \cdot \widetilde{RC}_{bl} + \sum_{b \in B} \sum_{j \in J} \sum_{k \in K} \sum_{s \in S} \pi_s \cdot y1_{kjs} \cdot DE_{bks} \cdot S_{bs} \cdot \widetilde{CC}_b \\
& + \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot (x1_{bkjls} + q_{bjls} - q1_{bjs}) \cdot \theta_{bs} \cdot \widetilde{DIC}_b - \sum_{b \in B} \sum_{j \in J} \sum_{s \in S} \pi_s \cdot q1_{bjs} \cdot \widetilde{SP}_{bj}
\end{aligned} \tag{4.8}$$

The second objective function is to maximize the total expected collection coverage. In other words, maximization of the coverage of collected batteries through opened collection centers and/or hybrid facilities is aimed with this goal. Formulation of this goal is motivated based on the well-known problem in the literature as “*maximal coverage problem*”. Maximal coverage location problem (MCLP) is defined by Davari et al. (2011) as investigating the location of a number of facilities on a network in order to maximize the covered population. For covering a population, at least one facility must be opened within a pre-defined distance of it. To the best of our knowledge, this objective has not been addressed by the previous works so far and is very vital in the case of scarce financial resources.

$$E[Total\ Collection\ Coverage] = \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{s \in S} \pi_s \cdot DE_{bks} \cdot S_{bs} \cdot y1_{kjs} \tag{4.9}$$

Table 4.2 Mathematical nomenclature for the proposed MILP model

<i>Indices and sets</i>	
b	set of battery type $b \in B$
c	set of component type $c \in C$
i	set of new battery manufacturers $i \in I$
j	set of potential depot such as regional wholesalers, collection centers or hybrid facilities $j \in J$
k	set of battery dealers, retailers or authorized automotive services $k \in K$
l	set of potential licensed recycling facilities $l \in L$
v	set of vendors $v \in V$
s	set of potential scenarios $s \in S$
<i>Model parameters</i>	
<i>Stochastic parameters</i>	
DE_{bks}	demand of battery dealer or retailer k for battery type- b in scenario s
S_{bs}	returned fraction of demand for battery type- b from battery dealers or retailers in scenario s
θ_{bs}	disposal rate for battery type- b over scenario s (ratio for inappropriate condition of batteries for recycling)
π_s	occurrence probability of scenario s
<i>Possibilistic parameters</i>	
$\widetilde{f1}_j$	opening cost of the regional wholesaler j
$\widetilde{f2}_j$	opening cost of the collection center j
$\widetilde{f3}_j$	opening cost of the hybrid facility j
$\widetilde{f4}_l$	opening cost of the licensed recycling facility l
$\widetilde{PRC}_b$	production cost of one unit of battery type- b in each new battery manufacturer
$\widetilde{TC}_b$	transportation cost of one unit of battery type- b per kilometer
$\widetilde{TC1}_b$	transportation cost of one unit of used battery type- b per kilometer
$\widetilde{TC}_c$	transportation cost of material/component type- c in kilograms per kilometer
$\widetilde{PUC}_{cvi}$	purchasing cost of material/component type c in kilograms from vendor v for manufacturer i
$\widetilde{PC}_{bj}$	purchasing cost of one unit of used battery type- b from any scrap dealer for depot j
$\widetilde{SP}_{bj}$	selling price of one unit of used battery type- b from depot j to any scrap dealer
$\widetilde{RC}_{bl}$	recycling cost per unit of used battery type- b in licensed recycling facility l
$\widetilde{CC}_b$	collection cost per unit of spent battery type- b
$\widetilde{DIC}_b$	disposal cost per unit of un-recyclable battery type- b
$\widetilde{\gamma}_b$	recycling rate for battery type- b
$\widetilde{N}$	maximum number of opened collection centers and hybrid facilities
$\widetilde{DMAX}$	maximum allowable distance from a given regional wholesaler or hybrid facility to a battery dealer or retailer for new battery distribution
$\widetilde{D1MAX}$	maximum allowable distance from a given battery dealer or retailer to a collection center or hybrid facility for used battery collection
<i>Deterministic parameters</i>	
W_b	weight of the used battery type- b
ε_{cb}	percentage of contribution of material/component type- c for the used battery type- b
ρ_{cb}	amount of material/component type- c to produce one unit of new battery type- b
a_{jk}	binary parameter is equal to 1, if the distance between the battery dealer k and collection center or hybrid facility j is within the maximum acceptable distance. 0, otherwise
cap_{bj}^f	capacity of regional wholesaler j for forward flows of newly produced battery type- b
$hcap_{bj}^f$	capacity of hybrid facility j for forward flows of newly produced battery type- b
cap_{bj}^r	capacity of collection center j for reverse flows of spent battery type- b
$hcap_{bj}^r$	capacity of hybrid facility j for reverse flows of spent battery type- b
$Prcap_{bi}$	production capacity of new battery manufacturer i for battery type- b
$REcap_{bl}$	recycling capacity of licensed recycling facility l for used battery type- b
$Vcap_{cv}$	supply capacity of vendor v for material/component type- c

Table 4.2 Mathematical nomenclature for the proposed MILP model (cont.)

$d1_{ij}$	the distance between new battery manufacturer i and depot j
$d2_{jk}$	the distance between depot j and battery dealer or retailer k
$d3_{jl}$	the distance between depot j and licensed recycling facility l
$d4_{li}$	the distance between licensed recycling facility l and new battery manufacturer i
M	an arbitrary set large number
<i>Decision variables</i>	
w_j	1, if a regional wholesaler is opened at location j ; 0, otherwise
c_j	1, if a collection center is opened at location j ; 0, otherwise
h_j	1, if a hybrid facility is opened at location j ; 0, otherwise
r_l	1, if a licensed recycling facility is opened at location l ; 0, otherwise
Q_{bis}	production quantity of battery type- b for new battery manufacturer i in scenario s
x_{bijks}	quantity of battery type- b shipped from new battery manufacturer i via regional wholesaler or hybrid facility j to the battery dealer k in scenario s
$x1_{bkjls}$	quantity of used battery type- b shipped from battery dealer k via collection center j or hybrid facility j to the licensed recycling facility l in scenario s
$x2_{clis}$	quantity of material/component type- c shipped to new battery manufacturer i from licensed recycling facility l in scenario s
QP_{cvis}	amount of material/component type- c purchased from vendor v by new battery manufacturer i in scenario s
q_{bjls}	quantity of used battery type- b purchased by depot j (Hybrid facility or collection center) from any scrap dealer and sent to the licensed recycling facility l in scenario s
$q1_{bjs}$	quantity of used battery type- b sold to any scrap dealer from depot j in scenario s
RE_{bls}	recycling quantity of used battery type- b at licensed recycling facility l in scenario s
y_{jks}	1, if regional wholesaler or hybrid facility j serves battery dealer k for meeting its demand in the forward chain in scenario s ; 0, otherwise
$y1_{kjs}$	1, if collection center or hybrid facility j serves battery dealer k for collecting the returned batteries from this battery dealer in the reverse chain in scenario s ; 0, otherwise
y_{bjs}	1, if depot j purchases used battery type- b from any scrap dealer in scenario s ; 0, otherwise
$y1_{bjs}$	1, if depot j sells used battery type- b to any scrap dealer in scenario s ; 0, otherwise

The constraints of the proposed model are expressed by Equations (4.10) to (4.34).

$$\sum_{j \in J} c_j + h_j \leq \tilde{N} \quad \forall s \quad (4.10)$$

$$y1_{kjs} \leq a_{jk} \cdot (c_j + h_j) \quad \forall s, \forall j, \forall k \quad (4.11)$$

$$\sum_{k \in K} y_{jks} \leq M \cdot (h_j + w_j) \quad \forall s, \forall j \quad (4.12)$$

$$\sum_{j \in J} y1_{kjs} \leq 1 \quad \forall s, \forall k \quad (4.13)$$

$$\sum_{j \in J} y_{jks} = 1 \quad \forall s, \forall k \quad (4.14)$$

$$\sum_{k \in K} y_{jks} \cdot DE_{bks} \leq cap_{bj}^f \cdot w_j + hcap_{bj}^f \cdot h_j \quad \forall s, \forall b, \forall j \quad (4.15)$$

$$\sum_{i \in I} x_{bijks} = DE_{bks} \cdot y_{jks} \quad \forall s, \forall b, \forall k, \forall j \quad (4.16)$$

$$\sum_{k \in K} y1_{kjs} \cdot DE_{bks} \cdot S_{bs} + \sum_{l \in L} q_{bjls} - q1_{bjs} \leq cap_{bj}^r \cdot c_j + hcap_{bj}^r \cdot h_j \quad \forall s, \forall b, \forall j \quad (4.17)$$

$$\sum_{l \in L} x1_{bkjls} = y1_{kjs} \cdot DE_{bks} \cdot S_{bs} \quad \forall s, \forall b, \forall k, \forall j \quad (4.18)$$

$$w_j + c_j + h_j \leq 1 \quad \forall s, \forall j \quad (4.19)$$

$$\sum_{j \in J} \sum_{k \in K} x_{bijks} \leq Q_{bis} \quad \forall s, \forall b, \forall i \quad (4.20)$$

$$Q_{bis} \leq Prcap_{bi} \quad \forall s, \forall b, \forall i \quad (4.21)$$

$$\left\{ \sum_{k \in K} \sum_{j \in J} x1_{bkjls} + \sum_{j \in J} q_{bjls} - \sum_{j \in J} q1_{bjs} \right\} \cdot (1 - \theta_{bs}) \cdot W_b = RE_{bls} \quad \forall s, \forall b, \forall l \quad (4.22)$$

$$\sum_{i \in I} x2_{clis} = \sum_{b \in B} RE_{bls} \cdot \tilde{\gamma}_b \cdot \varepsilon_{cb} \quad \forall s, \forall c, \forall l \quad (4.23)$$

$$\sum_{l \in L} q_{bjls} \leq M \cdot y_{bjs} \quad \forall s, \forall b, \forall j \quad (4.24)$$

$$q1_{bjs} \leq M \cdot y1_{bjs} \quad \forall s, \forall b, \forall j \quad (4.25)$$

$$y_{bjs} + y1_{bjs} \leq 1 \quad \forall s, \forall b, \forall j \quad (4.26)$$

$$d2_{jk} \cdot y_{jks} \leq \widetilde{D\overline{MAX}} \quad \forall s, \forall j, \forall k \quad (4.27)$$

$$d2_{jk} \cdot y1_{kjs} \leq \widetilde{D1\overline{MAX}} \quad \forall s, \forall j, \forall k \quad (4.28)$$

$$\sum_{v \in V} QP_{cvls} + \sum_{l \in L} x2_{clis} = \sum_{b \in B} Q_{bis} \cdot \rho_{cb} \quad \forall s, \forall c, \forall i \quad (4.29)$$

$$RE_{bls} \leq REcap_{bl} \cdot r_l \quad \forall s, \forall b, \forall l \quad (4.30)$$

$$x1_{bkjls} + q_{bjls} \leq M \cdot r_l \quad \forall s, \forall b, \forall k, \forall j, \forall l \quad (4.31)$$

$$\sum_{i \in I} QP_{cvls} \leq Vcap_{cv} \quad \forall s, \forall c, \forall v \quad (4.32)$$

$$w_j, c_j, h_j, r_l, y_{jks}, y1_{kjs}, y_{bjs}, y1_{bjs} \in (0,1) \quad (4.33)$$

$$\text{All other variables are continuous and positive} \quad (4.34)$$

Constraint (4.10) limits the number of collection centers or hybrid facilities to be opened for spent battery returns in each scenario. Constraint (4.11) determines which battery returns are covered within the acceptable service distance. Service means collection of used batteries from the retailers/dealers. If no collection center or hybrid facility is located in the scenario s , the right hand side of that constraint will be zero and forces $y1_{kjs}$ to be equal to zero. According to the constraint (4.12), if a regional wholesaler or hybrid facility is opened, it may serve to any dealer or retailer. In other

words, there may be an outgoing flow, i.e., distribution operation, from this depot to the dealers. Constraint (4.13) assures that a battery dealer may be assigned to at most a single collection center or hybrid facility for spent battery returns for each scenario. Since these assignments may be impossible because of the logic of maximal covering problem, ≤ 1 is used in that constraint set. Constraint (4.14) assures that a battery dealer is assigned to a single regional wholesaler or hybrid facility for forward flow of newly produced batteries. In other words, demands of the battery dealers must be satisfied by a single regional wholesaler or hybrid facility. Constraint (4.15) limits the number of newly produced batteries shipped through the regional wholesaler or hybrid facility to its capacity of performing forward flows. Constraint (4.16) maintains that the demands of battery dealers' for newly produced batteries must be satisfied in each scenario. Constraint (4.17) restricts the number of returned batteries transferred through a collection center or hybrid facility to its capacity of performing reverse flows. Constraint (4.18) ensures that volume of returned batteries from a given dealer or retailer is the fraction of total demand of that dealer or retailer. Constraint (4.19) ensures that at most one type of facility (regional wholesaler, collection center or hybrid facility) can be opened at the potential depot locations in scenario s . Constraint (4.20) guarantees that the outgoing flows from a new battery manufacturer cannot exceed the production quantity at that manufacturer. Constraint (4.21) ensures that the production quantity of each battery type must not get over the production capacity of the new battery manufacturers. According to constraint (4.22), one can calculate the quantity of used batteries in weight that are recyclable. Constraint (4.23) is the conservation of flow constraint for the licensed recycling facilities. Constraint (4.24) and (4.25) provide that the variables related to quantities must take value in the case of used battery purchasing from the scrap dealers or sales of used batteries to the scrap dealers. Constraint (4.26) ensures that purchasing and selling operations for the same type of scrap batteries cannot be actualized simultaneously (in that single time period). At most one of these variables can take a value for each battery type, scenario and each collection center or hybrid facility. Constraints (4.27) and (4.28) assure that each regional wholesaler, collection center or hybrid facility should be located within acceptable proximity of battery dealers over scenario s . Constraint (4.29) is balance equation for the components that are used in the new battery production. Constraints

(4.30) and (4.32) are capacity constraints for the licensed recycling facilities and vendors, respectively. Constraint (4.31) makes sure that if a licensed recycling facility is opened at the candidate location, there may be incoming flows of used batteries from the collection centers, hybrid facilities or scrap dealers to this recycling facility. Constraint (4.33) represents the binary variables such as opening decisions for the facilities; assignment decisions for allocating battery dealers to the regional wholesalers, collection centers and hybrid facilities and decisions regarding scrap battery purchasing or sales.

4.3.2 Transformation of Hybrid Model into Equivalent Crisp and Stochastic Form

In order to transform the developed hybrid model into crisp equivalent and stochastic form, the method for solving fuzzy linear programming models which was proposed by Jimenez et al. (2007) is utilized. This method mainly depends on the “expected interval”, “expected value” of fuzzy numbers and as well as fuzzy ranking method of Jimenez (1996). The most important reason for choosing this technique is that one can achieve in a computationally efficient way of solving this possibilistic programming problems with its linearity and without any increments in objective functions and inequality constraints (Pishvae & Razmi, 2012). On the other hand, it is required one more constraint in the case of equality constraints (Peidro et al., 2009; Pishvae & Torabi, 2010). The constraints (4.8), (4.10), (4.23), (4.27) and (4.28) which involve possibilistic parameters are converted and the non-possibilistic constraints with the second goal are added to the model and remaining unalterable. The equivalent crisp α -parametric linear program including stochastic terms can be given as follows:

$$\begin{aligned}
E[Total CLSC Cost] = & \sum_{j \in J} \left(\frac{f1_j^{pes} + 2.f1_j^{mos} + f1_j^{opt}}{4} \right) \cdot w_j + \sum_{j \in J} \left(\frac{f2_j^{pes} + 2.f2_j^{mos} + f2_j^{opt}}{4} \right) \cdot c_j + \\
& \sum_{j \in J} \left(\frac{f3_j^{pes} + 2.f3_j^{mos} + f3_j^{opt}}{4} \right) \cdot h_j + \sum_{l \in L} \left(\frac{f4_l^{pes} + 2.f4_l^{mos} + f4_l^{opt}}{4} \right) \cdot r_l + \\
& \sum_{b \in B} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot Q_{bis} \cdot \left(\frac{PRC_b^{pes} + 2.PRC_b^{mos} + PRC_b^{opt}}{4} \right) + \sum_{b \in B} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot RE_{bls} \cdot \left(\frac{RC_{bl}^{pes} + 2.RC_{bl}^{mos} + RC_{bl}^{opt}}{4} \right) + \quad (4.35) \\
& \sum_{b \in B} \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{s \in S} \pi_s \cdot x_{bijks} \cdot \left(\frac{TC_b^{pes} + 2.TC_b^{mos} + TC_b^{opt}}{4} \right) \cdot (d1_{ij} + d2_{jk}) + \\
& \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot x1_{bkjls} \cdot \left(\frac{TC1_b^{pes} + 2.TC1_b^{mos} + TC1_b^{opt}}{4} \right) \cdot (d2_{jk} + d3_{jl}) +
\end{aligned}$$

$$\begin{aligned}
& \sum_{c \in C} \sum_{l \in L} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot x2_{clis} \cdot \left(\frac{TC_c^{pes} + 2 \cdot TC_c^{mos} + TC_c^{opt}}{4} \right) \cdot d4_{li} + \\
& \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot q_{bjls} \cdot \left(\frac{TC1_b^{pes} + 2 \cdot TC1_b^{mos} + TC1_b^{opt}}{4} \right) \cdot d3_{jl} + \\
& \sum_{c \in C} \sum_{v \in V} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot QP_{cvis} \cdot \left(\frac{PUC_{cvi}^{pes} + 2 \cdot PUC_{cvi}^{mos} + PUC_{cvi}^{opt}}{4} \right) + \\
& \sum_{b \in B} \sum_{j \in J} \sum_{k \in K} \sum_{s \in S} \pi_s \cdot y1_{kjs} \cdot DE_{bks} S_{bs} \cdot \left(\frac{CC_b^{pes} + 2 \cdot CC_b^{mos} + CC_b^{opt}}{4} \right) - \\
& \sum_{b \in B} \sum_{j \in J} \sum_{s \in S} \pi_s \cdot q1_{bjs} \cdot \left(\frac{SP_{bj}^{pes} + 2 \cdot SP_{bj}^{mos} + SP_{bj}^{opt}}{4} \right) + \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot q_{bjls} \cdot \left(\frac{PC_{bj}^{pes} + 2 \cdot PC_{bj}^{mos} + PC_{bj}^{opt}}{4} \right) + \\
& \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot (x1_{bkjls} + q_{bjls} - q1_{bjs}) \cdot \theta_{bs} \cdot \left(\frac{DIC_b^{pes} + 2 \cdot DIC_b^{mos} + DIC_b^{opt}}{4} \right) \\
& \sum_{j \in J} c_j + h_j \leq \alpha \cdot \left(\frac{N^{pes} + N^{mos}}{2} \right) + (1 - \alpha) \cdot \left(\frac{N^{mos} + N^{opt}}{2} \right) \quad \forall s
\end{aligned} \tag{4.36}$$

$$\sum_{i \in I} x2_{clis} \geq \sum_{b \in B} RE_{bils} \cdot \varepsilon_{cb} \cdot \left[\frac{\alpha}{2} \cdot \left(\frac{\gamma_b^{mos} + \gamma_b^{opt}}{2} \right) + \left(1 - \frac{\alpha}{2} \right) \cdot \left(\frac{\gamma_b^{pes} + \gamma_b^{mos}}{2} \right) \right] \quad \forall c, \forall l, \forall s \tag{4.37}$$

$$\sum_{i \in I} x2_{clis} \leq \sum_{b \in B} RE_{bils} \cdot \varepsilon_{cb} \cdot \left[\frac{\alpha}{2} \cdot \left(\frac{\gamma_b^{pes} + \gamma_b^{mos}}{2} \right) + \left(1 - \frac{\alpha}{2} \right) \cdot \left(\frac{\gamma_b^{mos} + \gamma_b^{opt}}{2} \right) \right] \quad \forall c, \forall l, \forall s \tag{4.38}$$

$$d2_{jk} \cdot y_{jks} \leq \alpha \cdot \left(\frac{DMAX^{pes} + DMAX^{mos}}{2} \right) + (1 - \alpha) \cdot \left(\frac{DMAX^{mos} + DMAX^{opt}}{2} \right) \quad \forall j, \forall k, \forall s \tag{4.39}$$

$$d2_{jk} \cdot y1_{kjs} \leq \alpha \cdot \left(\frac{D1MAX^{pes} + D1MAX^{mos}}{2} \right) + (1 - \alpha) \cdot \left(\frac{D1MAX^{mos} + D1MAX^{opt}}{2} \right) \quad \forall j, \forall k, \forall s \tag{4.40}$$

where α is a parameter indicates the feasibility degree of constraints.

4.4 Computational Case Study

In order to see the performance of the proposed hybrid stochastic and possibilistic multi-objective linear programming model, an illustrative example is generated as in Figure 4.2 based on inspiration from a lead/acid battery CLSC in Turkey. In the computational case study, there are three types of batteries, three types of components, two new battery manufacturers, three vendors to supply components/raw materials, thirty dealers or retailers with uniformly distributed yearly demands, thirteen potential sites for collection, distribution or both activities as hybrid facilities, four alternatives for licensed recycling facilities and finally twenty seven scenarios.

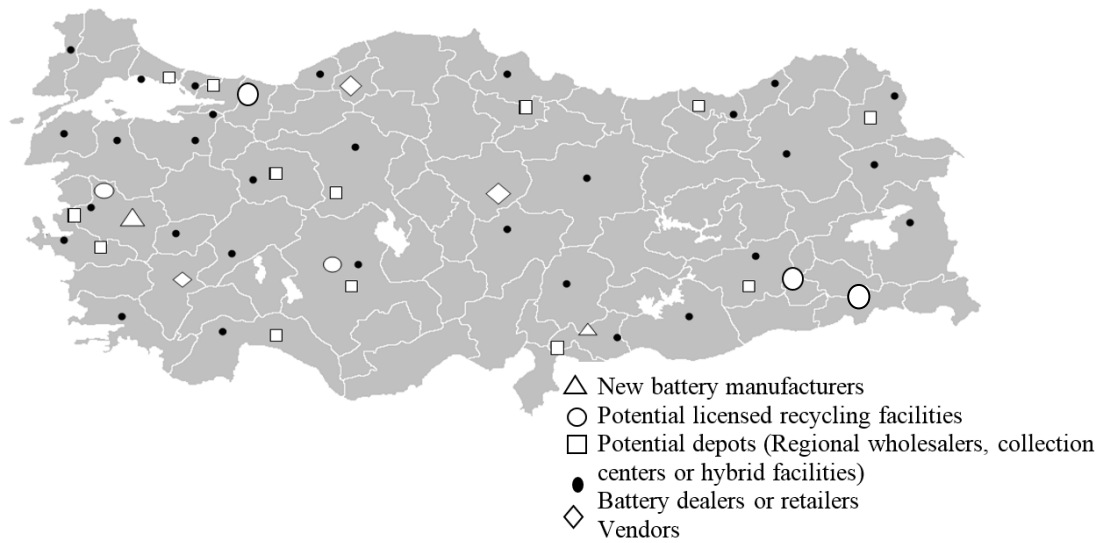


Figure 4.2 Configuration of the computational case study

In the solution phase of the problem, the proposed model is first solved with nominal data where all of the parameters are deterministic (see in Table 4.3). Discrete numbers of scenarios are generated with probabilities for the stochastic parameters as it can be seen in Figure 4.3 where the scenario #13 which has the greatest probability represents the deterministic model with nominal data. As it can be clearly understood, scenario index s is not required in the deterministic model.

Table 4.3 Nominal data for deterministic model

Parameters	Range of values
Demand forecasts of battery dealers (units)	Uniform distribution (500, 2500)
Unit production cost (\$/unit)	25-65
Unit transportation cost for newly produced batteries (\$/km.unit)	0.001-0.003
Unit transportation cost for used batteries (\$/km.unit)	0.002-0.004
Unit transportation cost for materials/components (\$/kg.unit)	0.008-0.015
Recycling cost (\$/kg.)	0.47-1.0
Unit collection cost (\$/unit)	2-5
Unit disposal cost (\$/unit)	1-3
Unit purchasing cost of used batteries from scarp dealers (\$/unit)	5-14
Unit selling price of used batteries to scrap dealers (\$/unit)	5-14
Unit purchasing cost for materials/components from the vendors (\$/kg)	0.5-4
Maximum number of opened collection centers and hybrid facilities	5
Fixed cost of opening regional wholesaler (\$)	150000-230000
Fixed cost of opening collection centers (\$)	60000-120000
Fixed cost of opening hybrid facilities (\$)	230000-390000
Fixed cost of opening licensed recycling facilities (\$)	400000-600000
Production capacity of battery manufacturers (units)	28000-56000
Capacity of regional wholesalers (units)	7500-15000
Capacity of collection centers (units)	10000-20000
Capacity of hybrid facilities for forward flows (units)	5250-10500
Capacity of hybrid facilities for reverse flows (units)	7000-14000
Capacity of licensed recycling facilities (kg.)	750000-4550000
Capacity of vendors (units)	50000-90000
Return fraction	50 %
Disposal rate	5%
Recycling rate	70 % - 80 %
Weight of used batteries (kg./unit)	15 - 35
Contribution percentages of materials/components	10 % - 55 %
Distances (km.)	0-1650
Max. acceptable distances (km.)	400-500

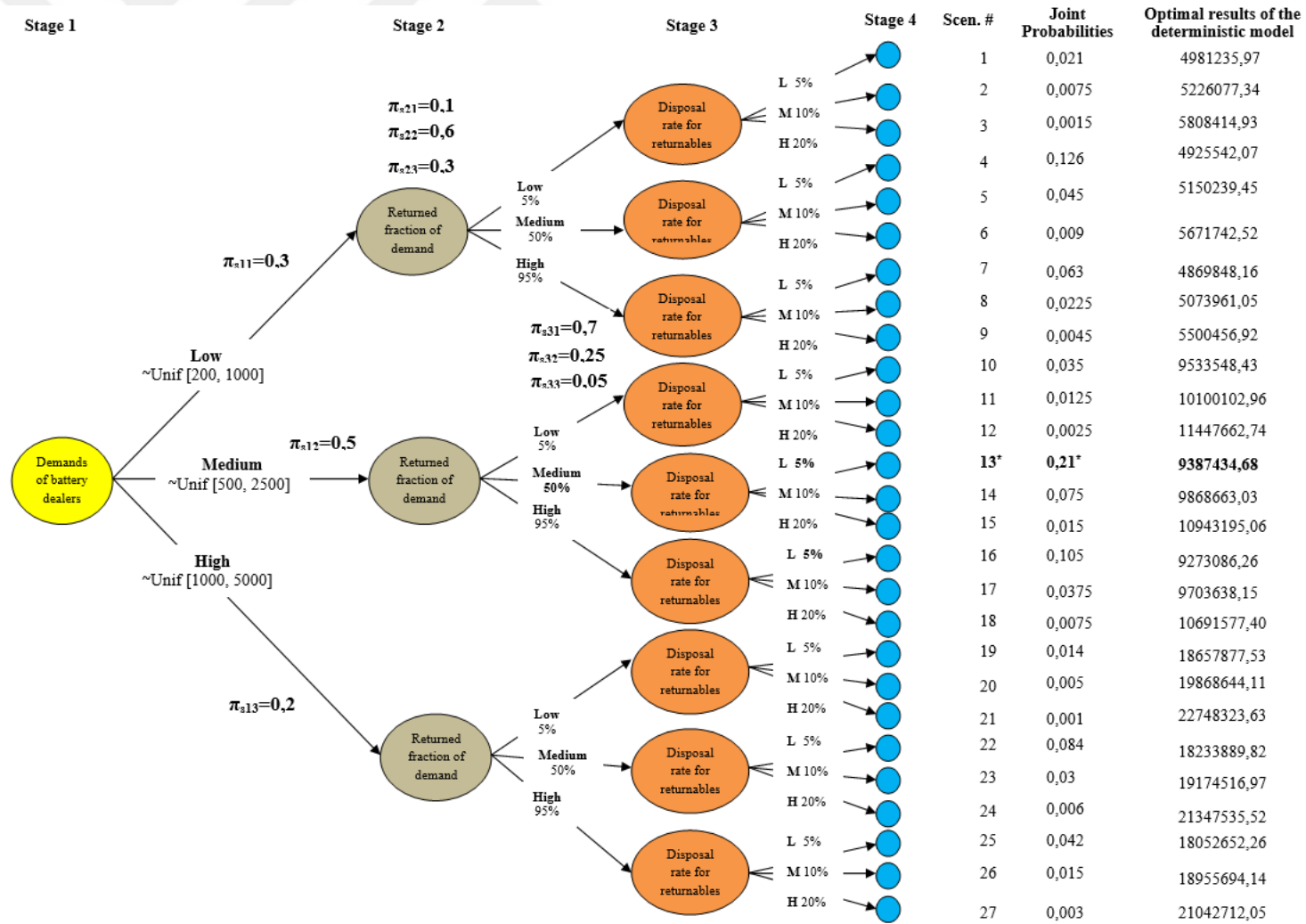


Figure 4.3 Scenario tree for stochastic model parameters

In addition, all of the possibilistic parameters are assumed to have most likely values of the defined possibility distributions. When the model is run under this nominal data through optimization software GAMS Rev 140 including CPLEX 9.0 product on an Intel Core i7 2 GHz IBM PC for each objective function independently, computational results are obtained as in the Table 4.4 for the deterministic model.

Table 4.4 Computational results under nominal data

	Total CLSC cost (Objective 1)	Total Collection Coverage (Objective 2)
Total number of variables	8177	8178
Total number of binary variables	901	901
Total number of constraints	8535	8537
Total number of iterations	6162	1128
Total cost of the CLSC	\$11026286.0455	\$16407000
Total collection coverage	10754 units	61564.5
CPU time (second)	0.125	0.124
Number of opened regional wholesalers	4	8
Number of opened collection centres	-	2
Number of opened hybrid facilities	1	3
Number of opened licensed recycling facilities	1	4

Moreover, corresponding optimal CLSC configurations for each objective are represented in Figures 4.4 and 4.5. These configurations reveal that the objectives constitute a conflict while designing the CLSC network.

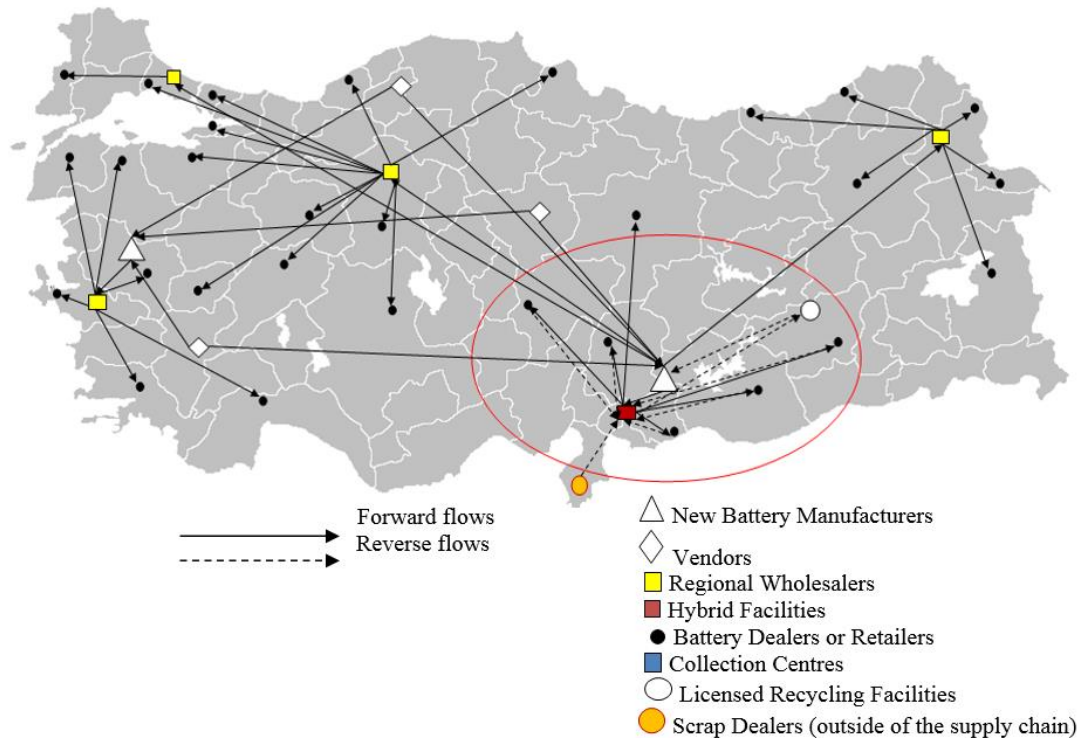


Figure 4.4 Optimal CLSC configuration under nominal data considering only total cost objective

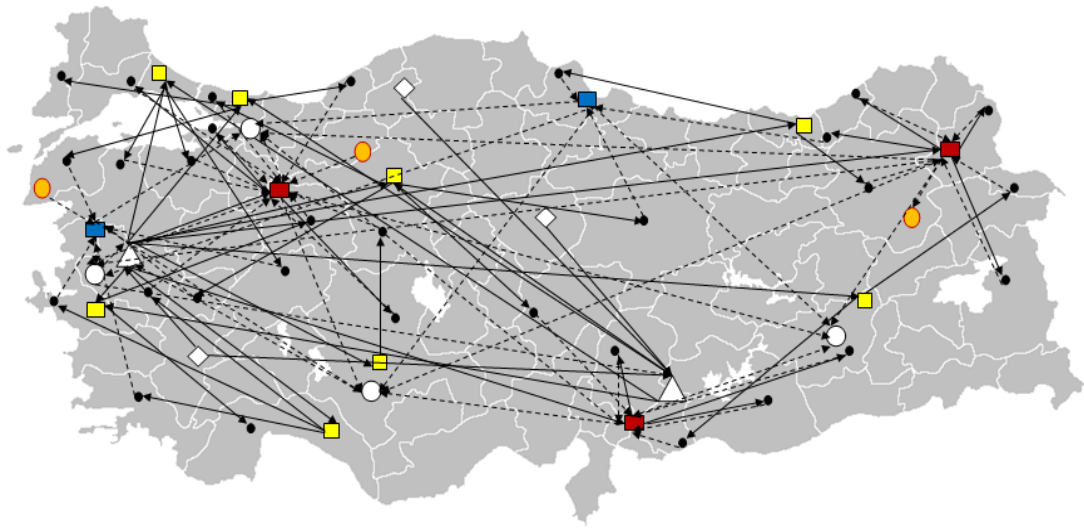


Figure 4.5 Optimal CLSC configuration under nominal data considering only total collection coverage

Later, possibilistic parameters are not included in the stochastic optimization model and again it is assumed that they have most likely values of the defined possibility distributions. Before solving this stochastic optimization model, each scenario is run as a deterministic model and the results are presented in Table 4.5 for each objective.

Table 4.5 Computational results under different scenarios for deterministic model

Scenario #	Total CLSC cost (Objective 1) (\$)	Total Collection Coverage (Objective 2) (units)	# of opened regional wholesalers (Obj1 / Obj2)	# of opened collection centers (Obj1 / Obj2)	# of opened hybrid facilities (Obj1 / Obj2)	# of opened licensed recycling facilities (Obj1 / Obj2)
1	5605851.585	2646.2	4 / 8	NA / 2	1 / 3	1 / 4
2	5773835.127	2646.2	4 / 8	NA / 2	1 / 3	1 / 4
3	6173212.628	2646.2	4 / 8	NA / 2	1 / 3	1 / 4
4	5585397.234	2646.2	4 / 8	NA / NA	1 / 5	1 / 4
5	5743382.661	2646.2	4 / 8	NA / NA	1 / 5	1 / 4
6	6118720.305	2646.2	4 / 8	NA / NA	1 / 5	1 / 4
7	5564942.883	50277.8	4 / 8	NA / 1	1 / 4	1 / 4
8	5712930.195	50277.8	4 / 8	NA / 1	1 / 4	1 / 4
9	5975109.207	50277.8	3 / 8	1 / 1	2 / 4	1 / 4
10	11417914.729	6156.45	4 / 8	NA / 2	1 / 3	1 / 4
11	11886773.254	6156.45	4 / 8	NA / 1	1 / 4	1 / 4
12	13001309.312	6156.45	4 / 8	NA / 1	1 / 4	1 / 4
13	11026286.046	6156.45	4 / 8	NA / 2	1 / 3	1 / 4
14	11760377.223	6156.45	5 / 8	2 / 2	NA / 3	1 / 4
15	12698469.199	6156.45	4 / 8	2 / 2	1 / 3	1 / 4
16	11190405.990	116972.55	5 / 8	2 / NA	NA / 5	1 / 4
17	11490250.028	116972.55	4 / 8	2 / 3	1 / 2	1 / 4
18	12108442.132	116972.55	3 / 8	3 / 1	2 / 4	1 / 4
19	22890641.987	13161.85	5 / 8	1 / 5	NA / NA	1 / 4
20	23966500.999	13161.85	5 / 8	1 / 1	NA / 4	1 / 4
21	26483466.466	13161.85	5 / 8	1 / 1	NA / 4	1 / 4
22	22587702.109	131618.5	5 / 8	2 / 1	NA / 4	1 / 4
23	23460743.447	131618.5	3 / 8	2 / NA	2 / 5	1 / 4
24	25412383.705	131618.5	2 / 8	2 / NA	3 / 5	1 / 4
25	22171657.968	250075.15	4 / 8	2 / NA	1 / 5	1 / 4
26	22826858.010	250075.15	3 / 8	2 / 1	2 / 4	1 / 4
27	24335539.053	250075.15	3 / 8	3 / 1	2 / 4	1 / 4

Afterwards, stochastic optimization model is run and the results are given in the following Table 4.6. The obtained solution is not optimal for all of the individual scenarios. The occurrence probability that is assigned to each scenario displays the importance of that scenario under uncertainty.

Table 4.6 Computational results of the stochastic optimization model

	Total CLSC cost (Objective 1)	Total Collection Coverage (Objective 2)
Total number of variables	219690	219690
Total number of binary variables	23209	23209
Total number of constraints	230501	230501
Total number of iterations	222436	72119
Total cost of the CLSC	\$12071480	\$18141430
Total collection coverage	38055.295 units	76749.029
CPU time (second)	960	120
Number of opened regional wholesalers	4	8
Number of opened collection centers	1	-
Number of opened hybrid facilities	1	5
Number of opened licensed recycling facilities	1	4

In the stochastic optimization model, one more collection center will be opened for only the consideration of the first objective function. On the other hand, additional two hybrid facilities will be opened in place of the collection centers in the stochastic optimization model when the second goal is optimized. When performance of the stochastic optimization model for each objective under each scenario is analyzed, both of the cost and collection coverage will also increase as demand of the battery dealers increases. Although the return fraction has a significant impact on the collection coverage, it has nearly no severe effect on the cost objective. Moreover, escalation in the disposal rate will cause cost increments and has no impact on the collection coverage as an expected result.

After solving the stochastic optimization model, possibilistic parameters are also taken into account by the hybrid model. Data related to these possibilistic parameters are given in Tables 4.7 and 4.8. Before solving this hybrid model, it is converted into the equivalent crisp and stochastic form as mentioned before. Computational results of the hybrid model according to the different minimum acceptable feasibility degrees (α -levels) are given in Table 4.9. As it can be seen from Table 4.9 that the values of both objective functions deteriorate when minimum acceptable feasibility degree is increased. The main reason of this decrements in collection coverage is to lose ability of opening more collection/hybrid facilities with more flexible allowable distances.

Table 4.7 Fixed opening cost for the potential depots (wholesalers, collection and hybrid facilities)

Location	Fixed cost of regional wholesalers (\$)	Fixed cost of collection centers (\$)	Fixed cost of hybrid facilities (\$)
Istanbul (1st region)	(150000, 170000, 180000)	(50000, 70000, 100000)	(220000, 230000, 260000)
Istanbul (2nd region)	(160000, 180000, 210000)	(70000, 90000, 120000)	(270000, 290000, 320000)
İzmir	(150000, 170000, 200000)	(40000, 60000, 90000)	(250000, 270000, 300000)
Ankara	(140000, 160000, 190000)	(80000, 100000, 130000)	(230000, 250000, 280000)
Eskisehir	(170000, 190000, 220000)	(80000, 100000, 130000)	(290000, 310000, 330000)
Konya	(180000, 200000, 230000)	(75000, 95000, 125000)	(310000, 330000, 350000)
Antalya	(210000, 230000, 260000)	(100000, 120000, 150000)	(270000, 290000, 310000)
Gaziantep	(170000, 190000, 220000)	(60000, 80000, 110000)	(270000, 290000, 320000)
Diyarbakır	(195000, 215000, 245000)	(88000, 108000, 138000)	(270000, 290000, 320000)
Trabzon	(200000, 220000, 250000)	(50000, 70000, 100000)	(320000, 340000, 360000)
Samsun	(210000, 230000, 260000)	(70000, 90000, 120000)	(370000, 390000, 420000)
Kars	(170000, 190000, 220000)	(75000, 85000, 115000)	(250000, 270000, 300000)
Manisa	(190000, 210000, 240000)	(90000, 110000, 140000)	(330000, 350000, 380000)

Table 4.8 Triangular fuzzy numbers for the other possibilistic parameters

Uncertain Parameter	Triangular Fuzzy Number
Maximum numbers of opened collection centers & hybrid facilities (units)	(3, 5, 7)
Maximum allowable distances for forward flows (km.)	(400, 500, 600)
Maximum allowable distances for collection (km.)	(300, 400, 500)
Recycling rate for battery type 1	(70%, 80%, 95%)
Recycling rate for battery type 2	(60%, 70%, 80%)
Recycling rate for battery type 3	(65%, 75%, 85%)

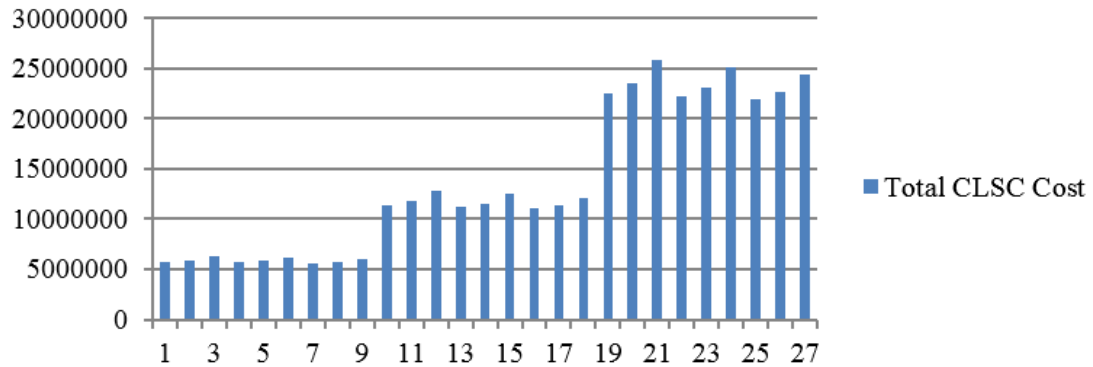
Actually, the value of minimum acceptable feasibility degree can be varied based on decision maker preferences. In other words, total expected CLSC cost and total expected collection coverage lose their importance when the decision maker decided to response to different uncertainty categories (stochastic and epistemic) with a higher confidence level.

Performance of the hybrid model for each objective under each scenario is displayed in Figures 4.6 and 4.7 where the minimum acceptable feasibility degree is set to 0.6. Figures 4.6 and 4.7 showed similar results with the stochastic optimization model's outcomes in terms of the effects of stochastic parameters changes. Corresponding optimal configurations of the hybrid model for the same feasibility degree ($\alpha=0.6$) are also presented in Figures 4.8 and 4.9. These figures are constructed for the scenario #13. Note in Figure 4.8 that recycled materials are only sent to the first battery manufacturer. Other manufacturer purchases the required materials from the vendors for new battery production. In Figure 4.9, in addition to battery purchasing from the scrap dealers, there are also battery sales to the scrap dealers.

Table 4.9 Summary of the results of hybrid model with different feasibility degrees

	Total CLSC cost (Objective 1)	Total Collection Coverage (Objective 2)
α -level (0.6)		
Total cost of the CLSC	\$11853420	\$97388000
Total collection coverage	37936.61 units	68891.7 units
CPU time (second)	2235	120
Number of opened regional wholesalers	4	9
Number of opened collection centers	1	3
Number of opened hybrid facilities	1	1
Number of opened licensed recycling facilities	1	4
α -level (0.8)		
Total cost of the CLSC	\$11910436.68	\$18599440
Total collection coverage	38055.3	68891.7 units
CPU time (second)	2645	203
Number of opened regional wholesalers	3	9
Number of opened collection centers	1	NA
Number of opened hybrid facilities	1	4
Number of opened licensed recycling facilities	1	4
α -level (1.0)		
Total cost of the CLSC	\$11969920	\$1515178000
Total collection coverage	38055.3	62240.63
CPU time (second)	3265	4367
Number of opened regional wholesalers	4	9
Number of opened collection centers	1	NA
Number of opened hybrid facilities	1	4
Number of opened licensed recycling facilities	1	4

Total CLSC Cost $\alpha=0.6$



Total Collection Coverage $\alpha=0.6$

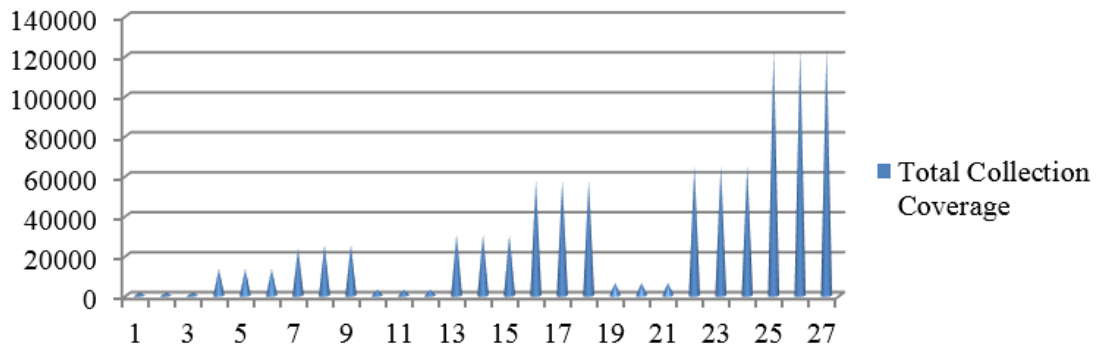


Figure 4.6 Computational results of hybrid model for each scenario by optimizing only total cost

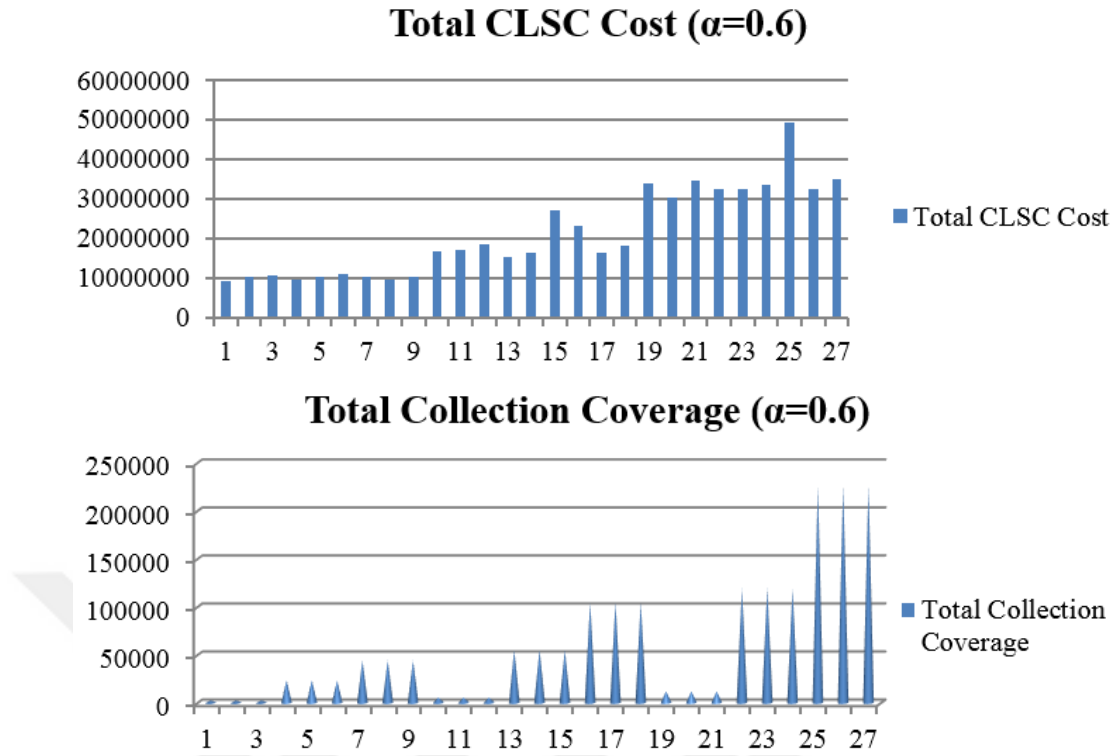


Figure 4.7 Computational results of hybrid model for each scenario by optimizing collection coverage

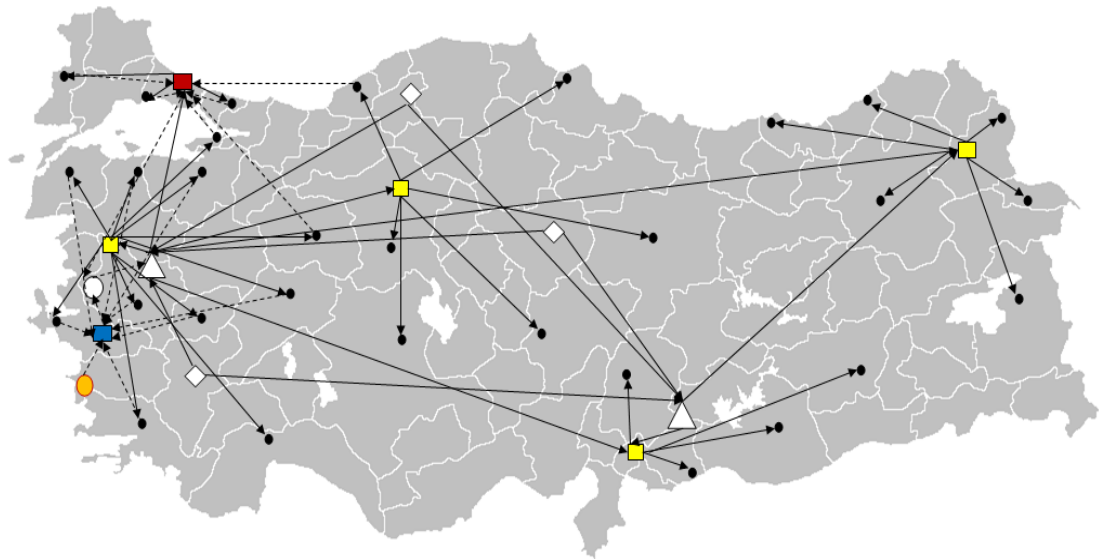


Figure 4.8 Optimal CLSC network for hybrid model in scenario#13 with only total cost ($\alpha=0.6$)

In comparison of the deterministic, stochastic and the hybrid model in an aggregated manner, randomness in the data (stochastic parameters) yields increases in cost values. Fortunately, when the epistemic uncertainty in data is taken into account (hybrid model), total cost of the system decreases. Besides, when different uncertainty categories in data are handled simultaneously, it is clear that total collection coverage

increases. However, total amounts of collected batteries in the result of hybrid model are fewer when compared to the stochastic optimization outcomes as depicted in Figure 4.10.

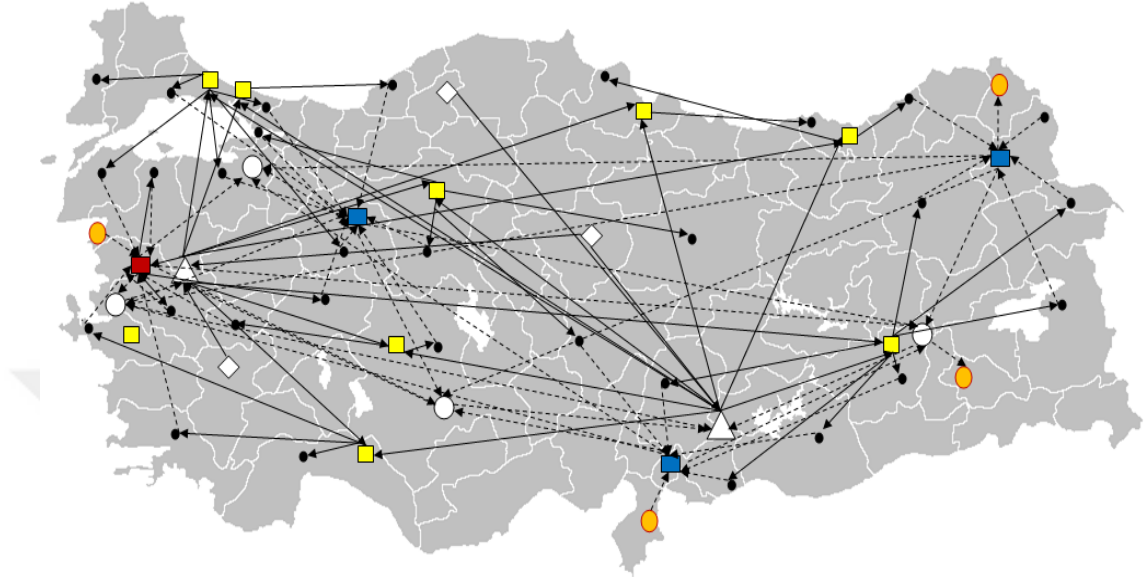


Figure 4.9 Optimal CLSC network for hybrid model in scenario#13 considering only collection coverage ($\alpha=0.6$)

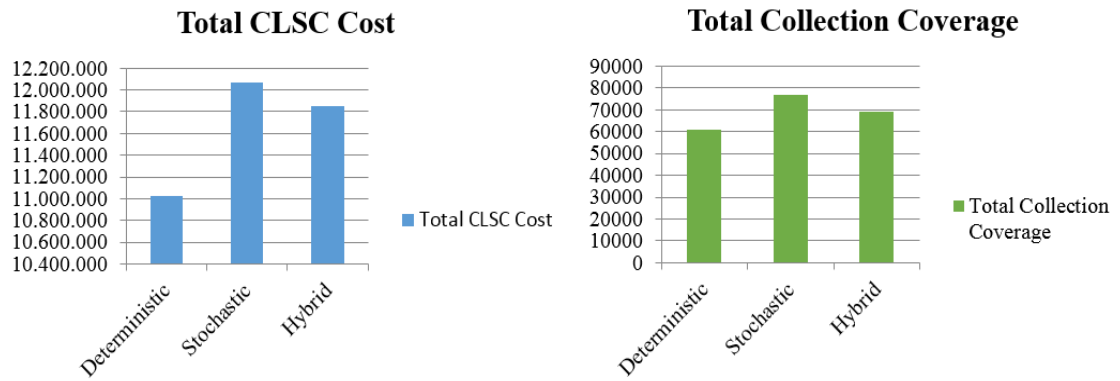


Figure 4.10 Comparison of the results without risk management issues

4.5 Improvements on Hybrid Model via Adapting Risk Management Metrics

The previously formulated objectives of the proposed hybrid model are appropriate goals for the risk-neutral decision makers and do not take into account the risk management issues. However, the decision maker(s) of a CLSC network design problem may be a risk-averse person and want to manage the risks besides improving the total expected CLSC cost and total expected collection coverage simultaneously

(You et al., 2009). Moreover, it should be noted here that when the CLSC network want to be designed under uncertainty, the financial risk and risk of collection related to the CLSC configuration should also be managed for providing useful managerial support to the decision makers. Therefore, additional objective(s) should be formulated or current objectives should be modified for managing these risks in an efficient and effective manner. In other words, this is required for obtaining a robust programming model which is able to take into consideration the decision maker(s)' favored risk aversion. In this section, four different risk measures such as Variability Index (VI), Downside Risk (DR) with deterministic and fuzzy targets and Conditional Value at Risk (CVaR) are applied and the results are compared. However, the variance management and probabilistic financial risk models are not utilized due to the aforementioned disadvantages in Section 4.2. In summary, different collection risk models besides financial risk distinct from the current literature is proposed for the first time in this chapter.

4.5.1 Financial and Collection Variability Index Models (FVI & CVI)

Variability index model was defined by Ahmed and Sahinidis (1998) as “*the minimization of the positive deviation between the scenario costs and the expected cost*”. If the scenario cost is greater than the expected cost, a non-negative auxiliary variable (Δ_s) is introduced and equal to the positive difference between them, otherwise will be equal to zero. Similarly, for collection coverage goal, another variable namely (β_s) is defined. If the scenario coverage is less than the expected collection coverage, this variable is equal to the positive difference between them, otherwise will also be zero. In this respect, financial and collection variability index models (FVI & CVI) can be presented as follows:

$$\text{Minimize } E[\text{Total CLSC Cost}] + \rho \cdot \sum_{s \in S} \pi_s \cdot \Delta_s \quad (4.41)$$

$$\Delta_s \geq \text{Cost}_s - \left(\sum_{s \in S} \pi_s \cdot \text{Cost}_s \right) \quad (4.42)$$

$$\text{Constraint set (4.10) - (4.33) and } \Delta_s \geq 0 \quad \forall s \in S \quad (4.43)$$

$$\text{Maximize } E[\text{Total Collection Coverage}] - \rho \cdot \sum_{s \in S} \pi_s \cdot \beta_s \quad (4.44)$$

$$\beta_s \geq \left(\sum_{s \in S} \pi_s \cdot \text{Coverage}_s \right) - \text{Coverage}_s \quad (4.45)$$

$$\text{Constraint set (4.10) - (4.33) and } \beta_s \geq 0 \quad \forall s \in S \quad (4.46)$$

where ρ is the weighted parameter. In these models, objective functions represent weighted sum between total expected CLSC cost/collection coverage and expected FVI & CVI, respectively. A trade off can be made between the total expected CLSC cost and the cost variability index (CVI) by using the different values of the weighted parameter. In this research, the weighted parameter is taken as 2.0 as in the study of You et al. (2009). Different from their study, another value that is close to zero ($\rho = 0.8$) is also considered. As sure enough, it is observed that when the value of this parameter approximates to zero, obtained total expected CLSC cost and/or collection coverage will gain similar values with the hybrid model results (before managing the variability index). Firstly, the FVI model is solved with all of the constraints in Section 4.3.1. Results for managing the FVI & CVI with different weighted parameters (ρ) and feasibility degrees (α) are given in Tables 4.10 and 4.11.

Table 4.10 Results for managing the financial variability index (FVI)

	$\alpha = 0.6$		$\alpha = 0.8$		$\alpha = 1.0$	
	$\rho = 0.8$	$\rho = 2.0$	$\rho = 0.8$	$\rho = 2.0$	$\rho = 0.8$	$\rho = 2.0$
Objective value (Minimizing the sum of expected cost and financial variability index) (\$)	13562269	16624264.28	13630000.12	16460002.79	1370754.66	16296994.83
Total expected CLSC cost (\$)	11853848.7	12352697.04	11910436.68	120270456.9	11969927.89	11969927.89
Total expected collection coverage (units)	37898.9	38055.3	38055.3	41656.16	38055.3	38055.3
Cost variability index (\$)	2135534.7	2135783.6	2149454.3	2216478.5	2163533.5	2163553.5
CPU time (seconds)	5548.5	4687.49	1153.03	46758.97	66125.3	15225.5

Table 4.11 Results for managing the collection variability index (CVI)

	$\alpha = 0.6$		$\alpha = 0.8$		$\alpha = 1.0$	
	$\rho = 0.8$	$\rho = 2.0$	$\rho = 0.8$	$\rho = 2.0$	$\rho = 0.8$	$\rho = 2.0$
Objective value (maximizing the difference between expected coverage and collection variability index) (units)	52174.32	31800.36	52174.33	31800.36	47506.31	29183.97
Total expected CLSC cost (\$)	12607632.9	321604312.5	34074618.22	17834983.2	866750346.5	520393015
Total expected collection coverage (units)	68891.7	55061.9	68891.7	55062	62240.63	51125.5
Collection variability index (units)	20896.7	11630.8	20896.72	11630.8	18417.9	10970.7
CPU time (seconds)	145.7	6584.8	215.8	2961.8	681.1	33390.2

As it can be seen from these Tables 4.10 and 4.11, when more importance is given to FVI and CVI, (weight coefficient is increased), total expected CLSC cost will also increase and total expected collection coverage will decrease as a result of risk management. Similarly, when the feasibility degree of the constraints (α -level) is increased, total expected CLSC cost increases when more importance is given to the total expected CLSC cost ($\rho = 0.8$). However, when $\rho = 2.0$ or minimizing the FVI is intended as the main goal, total expected CLSC cost decreases. For managing the CVI, when both of the weighted parameter and feasibility degree are increased, total expected coverage will decrease as an expected result. A detailed cost and coverage distributions before and after managing the financial and collection variability indexes are given by the following Figure 4.11 for $\alpha = 0.6$ and $\rho = 2.0$. This figure shows that after managing the financial variability index, the percent of scenarios which are close to the total expected CLSC cost (\$11853420) will increase. Additionally, after managing the CVI, percent of scenarios which have more than 50,000 units of collection coverage for the spent batteries will also increase.

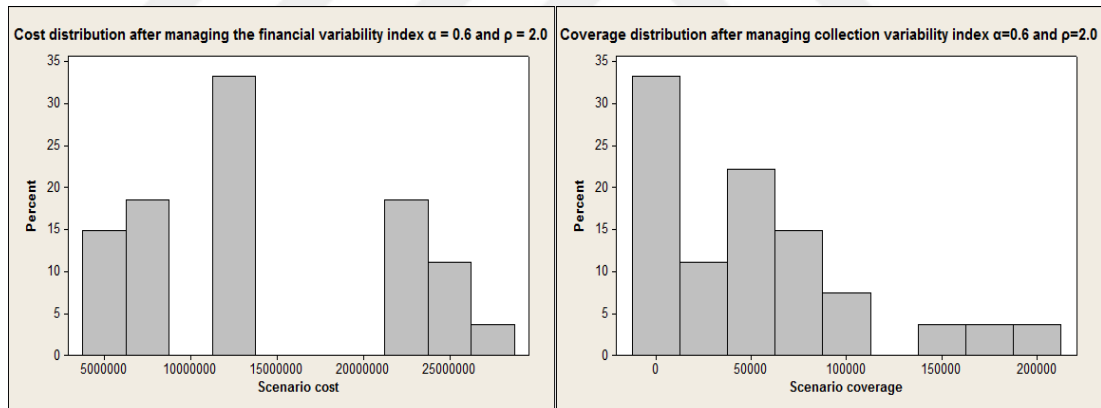


Figure 4.11 Histogram of cost and coverage distribution after managing financial and collection variability indexes (FVI and CVI)

4.5.2 Financial and Collection Downside Risks with Deterministic and Fuzzy Targets (FDR and CDR)

Downside risk measure provides lower probability of high cost or higher probability of low cost. Firstly, a positive deviation variable (δ_s and/or θ_s) which represents the difference between predetermined target Ω and the scenario cost or coverage is introduced. If the scenario cost is less than the target value, this positive deviation is

equal to zero. Otherwise, it will be equal to positive difference between them. Correspondingly, if the scenario collection coverage is greater than the target value, this positive deviation will be again equal to zero. Briefly, this risk measure contributes to objective functions under undesired circumstances. The formulations of the compact linear mathematical model for the financial and collection downside risks (FDR and CDR) with deterministic targets can be given as follows:

$$\text{Minimize } DRisk(x, \Omega) = \sum_{s \in S} \pi_s \cdot \delta_s \quad (4.47)$$

$$\delta_s \geq Cost_s - \Omega \quad (4.48)$$

$$\text{Constraint set (4.10) - (4.33) and } \delta_s \geq 0 \quad \forall s \in S \quad (4.49)$$

$$\text{Minimize } DRisk(x, \Omega) = \sum_{s \in S} \pi_s \cdot \theta_s \quad (4.50)$$

$$\theta_s \geq \Omega - Coverage_s \quad (4.51)$$

$$\text{Constraint set (4.10) - (4.33) and } \theta_s \geq 0 \quad \forall s \in S \quad (4.52)$$

It should be noted that these risk values are not probabilities as in the probabilistic financial risk metric, they are described by the same units (\$ or units) with the goals. Downside risk metric determines certain target values for the objectives. However, determination of these target values in a definite way or implicitly is generally a difficult task for the decision makers since the lack of some information or uncertainty. Therefore, these target values should be stated imprecisely and taken as fuzzy data. Therefore, the proposed fuzzy version of downside risk model can be given as follows:

$$\text{Minimize } DRisk(x, \tilde{\Omega}) = \sum_{s \in S} \pi_s \cdot \delta_s \quad (4.53)$$

$$\delta_s \geq Cost_s - \left\{ \alpha \cdot \frac{(\Omega_{pes} + \Omega_{mos})}{2} + (1 - \alpha) \cdot \frac{(\Omega_{mos} + \Omega_{opt})}{2} \right\} \quad (4.54)$$

$$\text{Constraint set (4.10) - (4.33) and } \delta_s \geq 0 \quad \forall s \in S \quad (4.55)$$

$$\text{Minimize } DRisk(x, \tilde{\Omega}) = \sum_{s \in S} \pi_s \cdot \theta_s \quad (4.56)$$

$$\theta_s \geq \left\{ \alpha \cdot \frac{(\Omega_{mos} + \Omega_{opt})}{2} + (1 - \alpha) \cdot \frac{(\Omega_{pes} + \Omega_{mos})}{2} \right\} - Coverage_s \quad (4.57)$$

$$\text{Constraint set (4.10) - (4.33) and } \theta_s \geq 0 \quad \forall s \in S \quad (4.58)$$

Before solving this fuzzy risk model, transformation process of Jimenez et al. (2007) should be performed as in Section 4.3.2. It is worthwhile that the corresponding formulations given in Equations (4.53) – (4.58) represent the converted form of the fuzzy risk model into the crisp equivalent one. In the downside risk model with fuzzy targets, it is assumed that following triangular fuzzy numbers: (\$11000000, \$12500000, \$15000000) and (40000 units, 60000 units, 70000 units) are determined by the decision maker for the uncertain target values. In the downside risk model with deterministic targets, decision maker sets the most likely values of the above fuzzy triangular numbers (\$12500000 and 60000 units) as the deterministic target values. When FDR and CDR are optimized separately with these deterministic and fuzzy targets, the computational results given in Tables 4.12 and 4.13 can be yielded.

Table 4.12 Results for managing financial downside risk with deterministic and fuzzy targets (FDR)

	$\alpha = 0.6$		$\alpha = 0.8$		$\alpha = 1.0$	
	<i>Deterministic</i>	<i>Fuzzy</i>	<i>Deterministic</i>	<i>Fuzzy</i>	<i>Deterministic</i>	<i>Fuzzy</i>
Total expected CLSC cost (\$)	12549291.19	12555154.09	12667361.51	12605292.12	12474183.1	12389385.16
Total expected collection coverage (units)	20552.5	20555.9	20881.89	22447.3	20436.2	23563.2
Financial downside risk (\$)	1993428.75	1983303.75	2018705.44	2119953.51	2060527.6	2242730.44
CPU time (seconds)	6650.26	4810.55	3240.8	13414.9	4182.1	2713.15

Table 4.13 Results for managing collection downside risk with deterministic and fuzzy targets (CDR)

	$\alpha = 0.6$		$\alpha = 0.8$		$\alpha = 1.0$	
	<i>Deterministic</i>	<i>Fuzzy</i>	<i>Deterministic</i>	<i>Fuzzy</i>	<i>Deterministic</i>	<i>Fuzzy</i>
Total expected CLSC cost (\$)	18026767.4	683085107.6	203844543.2	18179531.6	18120409.28	18183304.2
Total expected collection coverage (units)	48824.15	64376.65	54661.37	49996.61	50717.85	50251.8
Collection downside risk (units)	14939.28	14269.27	14939.28	16279.27	16916.67	20266.67
CPU time (seconds)	81.1	538.92	114.5	72.15	65.23	92.17

Figure 4.12 displays that managing the FDR provides more confidential solutions in terms of higher probability of low cost scenarios for the decision maker. When comparing FDR measures with deterministic and fuzzy targets, it is obviously seen from the same figure that they presented very nearby consequences. However, it is very important that when the uncertainty of the target value is taken into account, percent of scenarios around the pre-determined triangular fuzzy number will increase. In addition, more promising results are obtained for both total expected CLSC cost

(\$12389385.16) and total expected collection coverage (23563.2 units) from the FDR measure with fuzzy target value when the feasibility degree of constraints is set to 1.0.

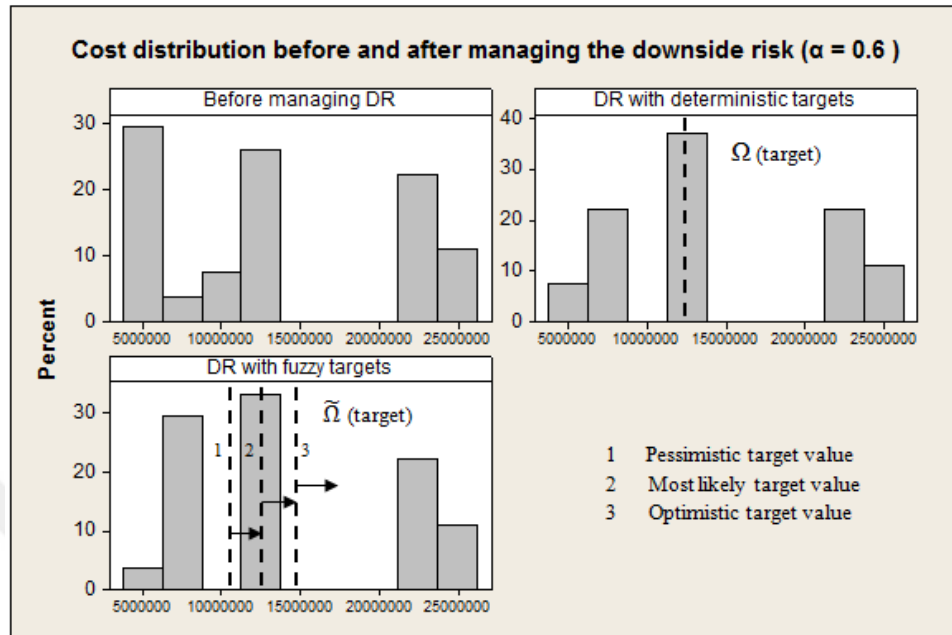


Figure 4.12 Histogram of cost distribution before/after managing financial downside risk (FDR)

As it can be seen from Table 4.12 and Figure 4.13, by managing only the collection downside risk, higher probability of high coverage scenarios, high total expected collection coverage (64376.65 units) and less collection downside risk value (14269.27 units) are provided in the case of fuzzy targets for $\alpha = 0.6$.

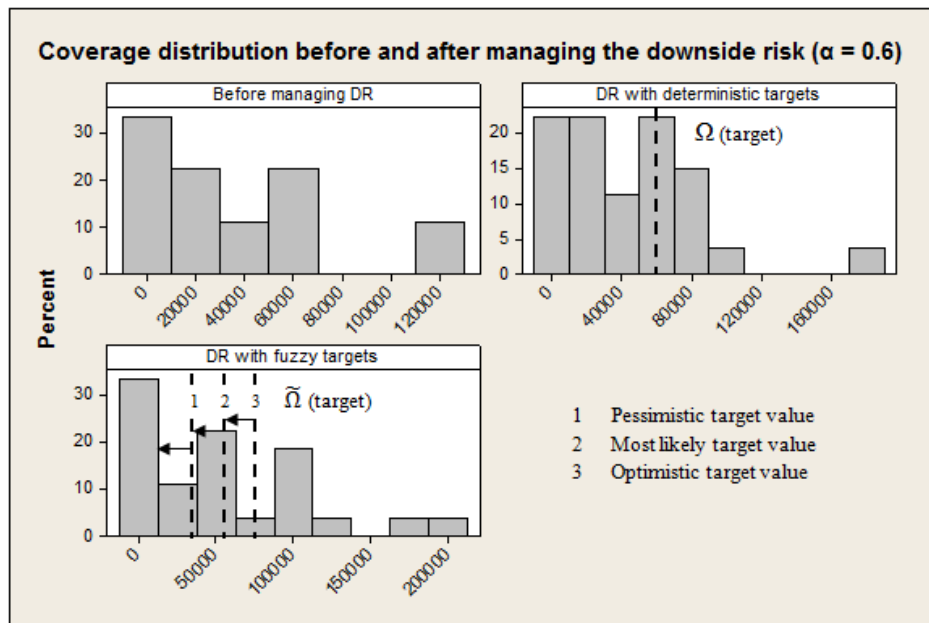


Figure 4.13 Histogram of coverage distribution before/after managing collection downside risk (CDR)

However, when the feasibility degree of constraints is increased, higher total expected collection coverage value and less downside risk value are provided in the case of deterministic targets (for $\alpha = 0.8$ and 1.0). Summary of the results showed that minimizing FDR causes lower collection coverage amounts. Similarly, optimizing CDR leads to higher costs and financial downside risk value.

4.5.3 Financial and Collection Conditional Value at Risk Models (FCVaR and CCVaR)

Conditional value at risk (β -CVaR) is the conditional expectation of losses above the amount ∇ with probability β . The definitions ensure that the Value at Risk (β -VaR) is never more than β -CVaR. Therefore, low β -CVaR must have low β -VaR as well (Uryasev, 2000). In other words, CVaR is weighted average of VaR and CVaR^+ , where CVaR^+ represents the “upper CVaR” or expected losses strictly exceeding VaR. Indeed, CVaR considers both probability and magnitude of loss. However, VaR takes only into account the probability of loss, not magnitude (Rockafeller & Uryasev, 2002; Uryasev, 2000). In other words, VaR only considers the extreme percentile of a gain/loss distribution without considering the magnitude of the loss. Therefore, a variant of VaR, namely CVaR has been widely utilized. Additionally, optimization process of CVaR can be very simple in terms of computational issues (Olson & Wu, 2013). It was also implied by Babazadeh et al. (2012) that CVaR is a measurement of risk related to an investment focusing on the less profitable outcomes. In detail, β -CVaR can be defined as “*minimization of the expected value of the costs in the $(1 - \beta) \times 100\%$ worst cases*” (Schultz & Tiedemann, 2006). Accounting the risks beyond VaR and measuring the downside risk are the most important features of CVaR (Rockafeller & Uryasev, 2002). In fact, CVaR aims to reduce probability of a portfolio which will incur large losses. In the light of the foregoing, mathematical model of the financial conditional value at risk (FCVaR) for the present CLSC network design problem can be presented as follows:

$$\text{Minimize } E[\text{Total CLSC Cost}] + \gamma \cdot \left(\nabla + \left(\frac{1}{1 - \beta} \right) \cdot \sum_{s \in S} \pi_s \cdot \varphi_s \right) \quad (4.59)$$

$$\begin{aligned}
& \sum_{j \in J} \left(\frac{f1_j^{pes} + 2.f1_j^{mos} + f1_j^{opt}}{4} \right) \cdot w_j + \sum_{j \in J} \left(\frac{f2_j^{pes} + 2.f2_j^{mos} + f2_j^{opt}}{4} \right) \cdot c_j + \\
& \sum_{j \in J} \left(\frac{f3_j^{pes} + 2.f3_j^{mos} + f3_j^{opt}}{4} \right) \cdot h_j + \sum_{l \in L} \left(\frac{f4_j^{pes} + 2.f4_j^{mos} + f4_j^{opt}}{4} \right) \cdot r_l + \\
& \sum_{b \in B} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot Q_{bis} \cdot \left(\frac{PRC_b^{pes} + 2.PRC_b^{mos} + PRC_b^{opt}}{4} \right) + \sum_{b \in B} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot RE_{bls} \cdot \left(\frac{RC_{bl}^{pes} + 2.RC_{bl}^{mos} + RC_{bl}^{opt}}{4} \right) + \\
& \sum_{b \in B} \sum_{l \in L} \sum_{j \in J} \sum_{k \in K} \sum_{s \in S} \pi_s \cdot x_{bijks} \cdot \left(\frac{TC_b^{pes} + 2.TC_b^{mos} + TC_b^{opt}}{4} \right) \cdot (d1_{ij} + d2_{jk}) + \\
& \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot x1_{bkjls} \cdot \left(\frac{TC1_b^{pes} + 2.TC1_b^{mos} + TC1_b^{opt}}{4} \right) \cdot (d2_{jk} + d3_{jl}) + \\
& \sum_{c \in C} \sum_{l \in L} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot x2_{clis} \cdot \left(\frac{TC_c^{pes} + 2.TC_c^{mos} + TC_c^{opt}}{4} \right) \cdot d4_{li} + \\
& \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot q_{bjls} \cdot \left(\frac{TC1_b^{pes} + 2.TC1_b^{mos} + TC1_b^{opt}}{4} \right) \cdot d3_{jl} + \\
& \sum_{c \in C} \sum_{v \in V} \sum_{i \in I} \sum_{s \in S} \pi_s \cdot QP_{cvis} \cdot \left(\frac{PUC_{cvi}^{pes} + 2.PUC_{cvi}^{mos} + PUC_{cvi}^{opt}}{4} \right) + \\
& \sum_{b \in B} \sum_{j \in J} \sum_{k \in K} \sum_{s \in S} \pi_s \cdot y1_{kjs} \cdot DE_{bks} \cdot S_{bs} \cdot \left(\frac{CC_b^{pes} + 2.CC_b^{mos} + CC_b^{opt}}{4} \right) - \\
& \sum_{b \in B} \sum_{j \in J} \sum_{s \in S} \pi_s \cdot q1_{bjs} \cdot \left(\frac{SP_{bj}^{pes} + 2.SP_{bj}^{mos} + SP_{bj}^{opt}}{4} \right) + \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot q_{bjls} \cdot \left(\frac{PC_{bj}^{pes} + 2.PC_{bj}^{mos} + PC_{bj}^{opt}}{4} \right) + \\
& \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} \sum_{s \in S} \pi_s \cdot (x1_{bkjls} + q_{bjls} - q1_{bjs}) \cdot \theta_{bs} \cdot \left(\frac{DIC_b^{pes} + 2.DIC_b^{mos} + DIC_b^{opt}}{4} \right) - \nabla - \varphi_s \leq 0
\end{aligned} \tag{4.60}$$

Constraint set (4.10) - (4.33) and $\nabla, \varphi_s \geq 0 \quad \forall s \in S$ (4.61)

The proposed CVaR model for maximizing collection coverage (CCVaR) can also be given as followings:

$$\text{Maximize } E[\text{Total Collection Coverage}] - \gamma \cdot \left(\nabla + (1/\beta) \cdot \sum_{s \in S} \pi_s \cdot \varphi_s \right) \tag{4.62}$$

Subject to:

$$\nabla - \varphi_s - \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{s \in S} \pi_s \cdot DE_{bks} \cdot S_{bs} \cdot y1_{kjs} \geq 0 \tag{4.63}$$

$$\text{Constraint set (4.10) - (4.33) and } \nabla, \varphi_s \geq 0 \quad \forall s \in S \tag{4.64}$$

where φ_s represents the maximum difference between the loss function and ∇ for a particular scenario s . β is a specific confidence level and also taken as 95%. In addition, weighting factor, γ is taken as 1.0 and 2.0 as in the study of Babazadeh et al. (2012),

respectively for each risk measure (FCVaR and CCVaR) in all of the computations. In the optimal solution, ∇ corresponds to the β -VaR.

Differently from the FCVaR, positive deviation between the VaR and loss function is computed in CCVaR. When the FCVaR and CCVaR are optimized separately with different degrees of feasibility and weighting factors, the following results given in Tables 4.14 and 4.15 are obtained.

Table 4.14 Results for managing the FCVaR model with different α -level and weighting factor

	$\alpha = 0.6$		$\alpha = 0.8$		$\alpha = 1.0$	
	$\gamma = 1.0$	$\gamma = 2.0$	$\gamma = 1.0$	$\gamma = 2.0$	$\gamma = 1.0$	$\gamma = 2.0$
Objective value (Minimizing the total expected cost with <i>FCVaR</i>) (\$)	15441048.64	18801063.99	15527522.76	18874617.15	15506190.99	18965892.1
Total expected CLSC cost (\$)	11963217.44	11924867.7	11923887.7	11978484.56	12046489.9	12046489.9
Total expected collection coverage (units)	14351.4	14351.4	21663.27	14351.4	11443.8	11443.82
CPU time (seconds)	45099	12998.72	1927.97	1141.5	2113.2	7778.8

Table 4.15 Results for managing proposed CCVaR model with different α -level and weighting factor

	$\alpha = 0.6$		$\alpha = 0.8$		$\alpha = 1.0$	
	$\gamma = 1.0$	$\gamma = 2.0$	$\gamma = 1.0$	$\gamma = 2.0$	$\gamma = 1.0$	$\gamma = 2.0$
Objective value (Maximizing the total expected coverage with <i>CCVaR</i>) (\$)	57328.68	46343.55	57328.68	46343.81	51504.27	41304.1
Total expected CLSC cost (\$)	1592575169.1	658650715.8	19304819.5	18447629.65	18122751.42	54204436.73
Total expected collection coverage (units)	68568.9	66475.3	68593.3	66725.3	61781.36	59152.8
CPU time (seconds)	796.3	2174.06	84.7	573.58	103.59	1379.78

Results of the FCVaR and CCVaR models demonstrated that minimizing total expected CLSC costs with FCVaR causes low collection coverage. In contrast, optimizing total expected collection coverage with CCVaR leads to high total expected CLSC costs. Moreover, increments in the feasibility degree and weighting factor cause escalation in relevant performance measures as a result of the risk management.

According to Table 4.14, as a result of risk management, total expected CLSC cost increases as the feasibility degree of constraints is increased. However, as it can be seen from Figure 4.14 that significant improvements in financial risks, especially in terms of the cost distribution may not be provided by increasing the weighting factor. Fortunately, slightly larger percent of low cost scenarios are obtained. Similar results are acquired after managing the collection risks with CCVaR measure. One can see from Table 4.15 that total expected collection coverage decreases in the case of

simultaneous increasing in both feasibility degree and weighting factor. As a result, using the given data in this chapter, it is found that CVaR measure has not an important effect on decreasing the percent of high cost and low coverage scenarios as it can be seen from Figures 4.14 and 4.15.

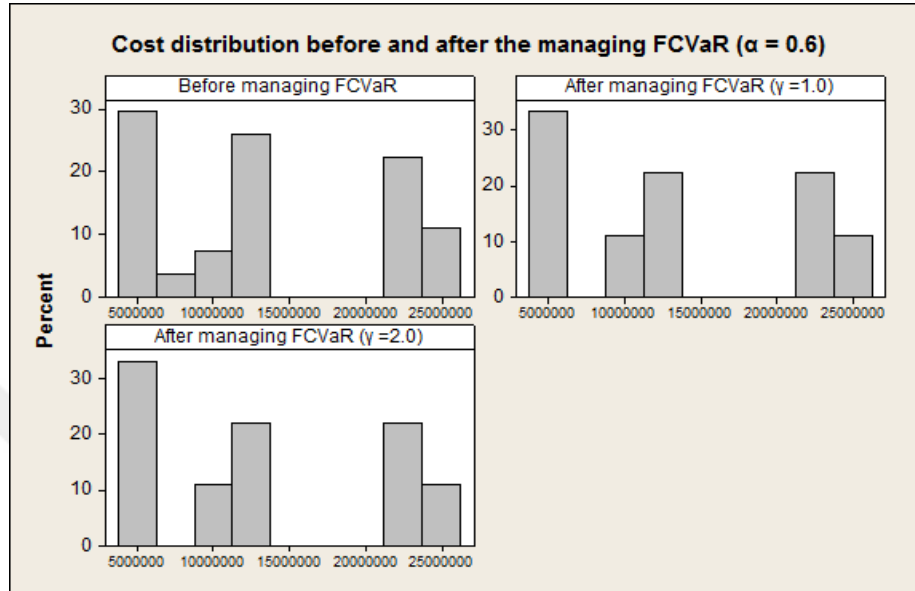


Figure 4.14 Histogram of cost distribution before/after managing financial conditional value at risk (FCVaR)

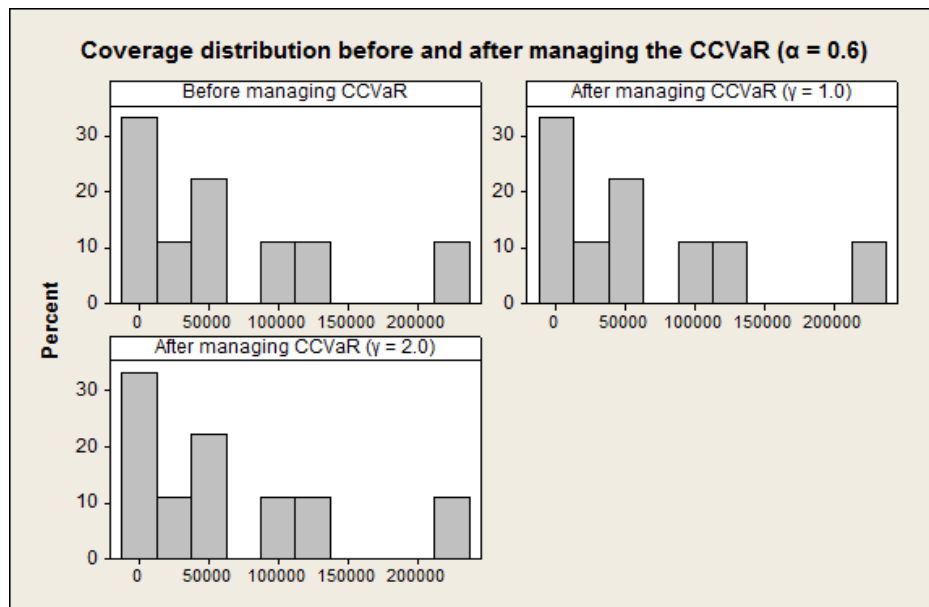


Figure 4.15 Histogram of coverage distribution before/after managing collection conditional value at risk (CCVaR)

Thus, comparison of CVaR with the other risk measures which was scheduled as a future work by Babazadeh et al. (2012) is carried out in this section. Moreover, one can see a detailed comparison for both financial and collection risk measures in Figures 4.16 and 4.17. When the results of all the risk measures are evaluated in terms of financial risk of the CLSC, it is clearly seen from Figure 4.16 that although downside risk measure with fuzzy targets presents relatively higher means for the total cost, this risk measure has the lowest standard deviation. In addition, it was also previously demonstrated by Figure 4.12 that the percentage of high cost scenarios in downside risk model with fuzzy targets becomes sparse compared to other risk metrics.

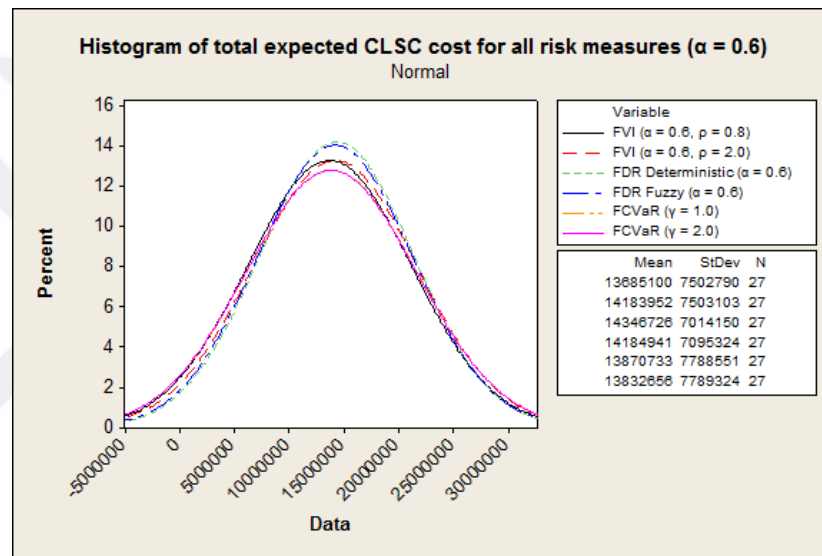


Figure 4.16 Histogram of the normally distributed scenario costs for each risk measure

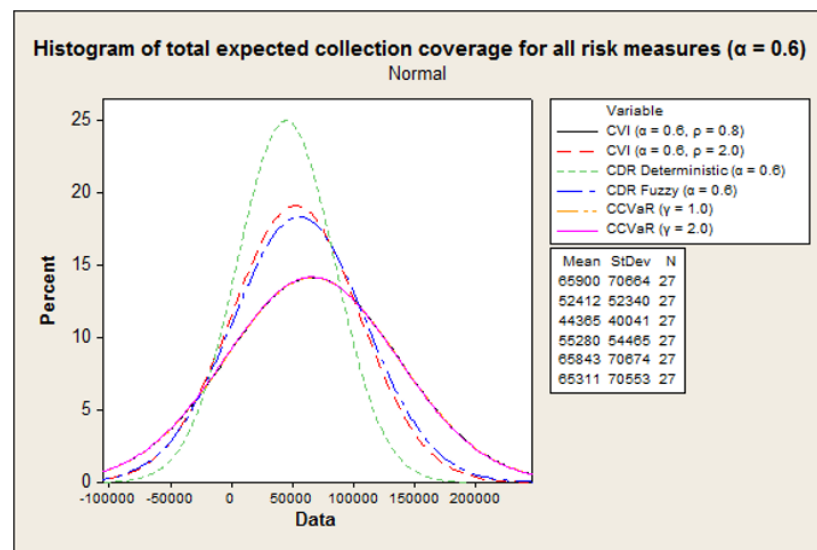


Figure 4.17 Histogram of the normally distributed scenario coverage for each risk measure

According to Figure 4.17, downside risk with deterministic target has the lowest standard deviation for collection coverage. However, this risk measure has also the lowest coverage mean which is an undesirable situation. Therefore, downside risk measure with fuzzy target or collection variability index ($\alpha = 0.6$ and $\rho = 2.0$) can be used by the decision maker(s) for higher levels of coverage mean and acceptable degree of standard deviation. Moreover, percent of high coverage scenarios in DR with fuzzy target is found to be greater compared to variability index measure.

In summary, a robust programming approach which can consider the attitude of decision maker(s) toward risk is provided by adapting the different risk management metrics. It is obviously seen from the cost and coverage distributions of different scenarios as depicted from Figures 4.11 to 4.15 that significant improvements can be provided in terms of increasing percent of low cost and high coverage scenarios after managing risks. This can be the best achieved by the proposed downside risk models with fuzzy targets which presented lowest standard deviation for the financial risks and highest level of coverage mean with acceptable degree of standard deviation.

4.6 Chapter Summary

In this chapter, a new multi-objective, multi-echelon, multi-product CLSC network design model is developed for a lead/acid battery industry considering both financial and collection risks under different uncertainty categories. It should be underlined that before managing the risks along the CLSC, one should pay attention to the uncertainty related to the handled problem effectively. In addition, different uncertainty categories, i.e., randomness and fuzziness might occur simultaneously in most of the real-life cases. For this reason, this chapter presents a hybrid scenario-based stochastic and possibilistic programming approach to CLSC network design for a better reflection of real-world applications. After handling different uncertainty categories jointly, most commonly used risk measures, i.e., variability index, downside risk and conditional value at risk models, in the literature are integrated into the proposed hybrid model. Apart from the available literature, these existing risk measures are revised for the collection coverage objective. Particularly for the downside risk, target values which are determined by the decision maker(s) are considered as uncertain and represented

by triangular fuzzy numbers as the values for these parameters contain some sort of ambiguity. Summary of the results showed that total expected CLSC cost increases and total expected collection coverage decreases after risk management. Furthermore, outcomes of the different risk measures suggest that using downside risk model with fuzzy targets will be the best choice in terms of both computational efficiency, handling uncertainty and solution quality. For the future works, Pareto optimal solutions can be found by applying a multi-objective optimization methodologies by considering total expected CLSC cost, collection coverage goals simultaneously with their risk issues. Additionally, development of a novel risk measure which is able to focus on both variability and targets or losses is also scheduled as a future research.



CHAPTER FIVE

A MULTI-OBJECTIVE SUSTAINABLE LOAD PLANNING MODEL FOR INTERMODAL TRANSPORTATION NETWORKS WITH A REAL-LIFE APPLICATION IN AN INTERNATIONAL LOGISTICS COMPANY

5.1 Chapter Introduction

In recent years, there is a rapid increase in intermodal transportation research area in the literature. The intermodal transportation can be defined as “*transportation of freights in one and same intermodal load unit (container, trailer, swap, box, body etc.) by using successive modes of transport (railway, maritime, road etc.) without any handling of the freights themselves when the transportation mode is altered*” (UNECE, 2009). There are some different terminologies for the multi-mode freight transportation systems in the scientific literature and global logistics industry such as multimodal, intermodal, co-modal and synchro modal transportation. Actually, multimodal transportation is the broadest term and covers all of the others (SteadieSeifi et al., 2014). In detail, the multimodal transportation is able to provide more efficient, reliable, flexible and sustainable way of freight transportation. Moreover, it can also support the transport flexibility and give the advantage of economies of scale to the logistics firms because of the more efficient usage of company resources resulting from the integration of different transportation modes. In fact, popularity of the intermodal transportation which is the most widely used multimodal system takes root from the problems of road congestion, environmental responsibilities and traffic safety. In other words, intermodal freight transportation planning problem have become a seriously studied research topic since its ability to increase traffic safety, customer satisfaction and decrease transportation costs, road congestion and environmental pollution. The intermodal freight transportation combines at least two different transportation modes in a single transport chain. In general, a transport chain mainly consists of three components namely pre-haulage, long-haulage and end-haulage which correspond to pick-up, door-to-door transfer and delivery services, respectively. The pre and end-haulages correspond to the trucking part of a transport chain and also named as drayage activities. These initial and final journey activities are mostly performed by road freight transportation due to the short travel distances.

Furthermore, drayage costs constitute the majority portion of the overall transportation costs even though the relatively short distance of truck movements. For this reason, drayage activities may have a significant impact on the profitability of intermodal transportation systems. In addition to these pre and end-haulage activities, transfer of the load units between any two terminals, i.e., seaports, railway stations and hubs, is called as long-haulage. For the long-haul freight transportation, many logistics companies typically prefer using the railway, airline, marine modes of transport and their combinations to the road freight transportation. A typical representation of an intermodal transport chain including short and long haulages can be portrayed as in Figure 5.1.

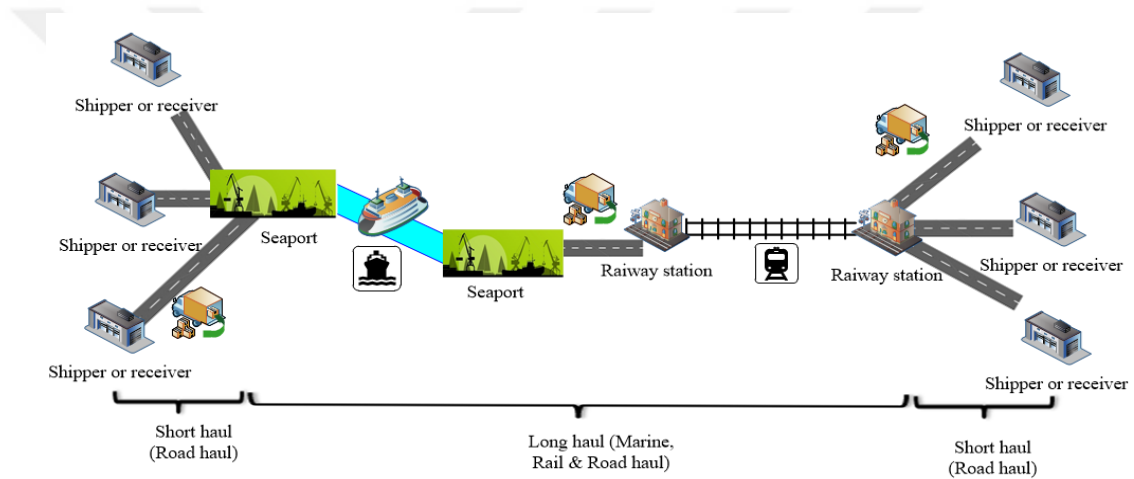


Figure 5.1 A simple depiction of road-marine-rail intermodal freight transportation

Nowadays, there has been a growing attention to model and solve load planning problems in intermodal transportation networks by both researchers and global logistics practitioners. Due to the growing importance of intermodal transportation, the freight transportation or load planning problems need to be solved by taking into account various complex decisions simultaneously, i.e., transportation mode and service type selection, load allocation, outsourcing, transshipment operations and frequency of maritime and railway services, which makes the problem more complicated. However, most of the existing researches in the literature were just emphasized on single mode freight transportation planning from the perspectives of logistics service providers or production companies. In other words, these available studies were approached to single mode freight transportation planning problems from the point of view of logistics service providers that provide only unimodal road freight

transportation or production companies which undertake the logistics activities by themselves. Therefore, many researchers focused on only the unimodal freight transportation and developed mathematical models for one mode only which are not able to handle intermodal flows on the logistics network. On the other hand, planning problems in intermodal freight transportation may become much more complex than the traditional unimodal transportation systems and thus require development of more comprehensive mathematical models, advanced Operational Research (OR) and Artificial Intelligence (AI) based solution methodologies.

The principle causes of this complexity can be explained as follows: (i) intermodal transportation composed of different transportation modes with their own specific characteristics related to the logistics infrastructure and multiple types of load units, (ii) management and control of the intermodal transportation systems may be more difficult because of including multiple decision makers with different objectives and decision levels, (iii) load planning may become more chaotic due to the large amounts of transportation units, truck and trailer fleet sizes, multiple time periods and high level of uncertainty. Besides, load plans for all of the transportation modes should be optimized in an integrated manner instead of optimizing each mode separately, (iv) finally, data exchange is a challenging task in intermodal transportation since the limited data availability, large problem dimension and information traits, high computational effort etc. These problematic issues also increase the complexity of decision support tools which are needed for load/freight planning activities of such a complicated intermodal transportation systems and introduce attractive research topics/future opportunities for OR researchers (Macharis & Bontekoning, 2004; SteadieSeifi et al., 2014; Caris et al., 2008; Caris et al., 2013). Although there are numerous studies on the logistics network design, transportation mode and service type selection, hub/terminal location and routing problems, there is still a lack of studies which utilize advanced OR and AI techniques in the literature for planning problems in intermodal transportation networks. Fortunately, load planning or intermodal freight transportation planning problem arises as a new research area in recent years because of increasing interests to multimodal transportation systems by the logistics sector all over the world. Conversely, most of the papers in this field presented hypothetical case studies instead of real-life applications. Moreover, they generally took into account the

transport cost, damage risks of hazardous materials and travel time-related objectives. There are a few studies which aim at minimizing the environmental effect resulting from all of the utilized transportation modes (Bauer et al., 2010; Ezabadi & Vergara, 2016). Besides, environmental aspect of the intermodal transportation systems was highlighted as current research trends by Caris et al. (2013) since it plays an important role in policy making. Therefore, multi-objective intermodal freight transportation planning which considers the trade-off between cost, time and environmental issues will merits more research. On top of all this, development of decision support systems based on advanced optimization models and innovative applications of AI techniques was given as future directions by Macharis and Bontekoning (2004) for intermodal freight transportation planning problems.

Based on these research motivations, this chapter presents a novel mixed-integer programming model for a multi-objective, multi-mode and multi-period freight transportation planning problem of an international logistics company in Turkey. In other words, a sustainable load planning model is developed based on network flow modeling for tactical intermodal freight transportation planning activities. The proposed model incorporates some essential decisions on transportation mode and service type selection, periodic load allocation, outsourcing, transshipment operations, maritime and railway itineraries and their frequency, utilization rates of Ro-Ro vessels etc. The usage of different types of marine transport services (by company-owned Ro-Ro vessels or other logistics service providers' Ro-Ro vessels) and distinct rail transport services (by block trains with fixed time schedules or public trains with flexible time schedules) are also included within the proposed model. In addition to minimize the overall transportation costs, maximal customer satisfaction and environmental consciousness are also intended by minimizing total transit times and CO₂ emissions, respectively. Thus, effective and efficient load plans can be generated by making use of the proposed model in a more sustainable manner. Apart from the existing studies in the literature, the proposed model takes into account the importation and exportation of loads simultaneously to satisfy the transport demands of the customers. Moreover, consolidation and/or exchange of load units at the transshipment seaports and railway stations are also taken into consideration in order to balance the import and export flows along the intermodal logistics network. For model verification

and validation, the proposed model is applied to a real-life case study of a large sized international logistics company in Turkey. In order to present applicable compromise solutions to the company experts, different multi-objective optimization methods such as compromise programming, fuzzy goal programming with different importance and priorities, interactive fuzzy goal programming and weighted additive fuzzy goal programming are implemented under both crisp and uncertain environments. The computational analysis have shown that effective and efficient load plans can be generated by making use of the proposed model in terms of economic, customer satisfaction and environmental objectives. In detail, it is proved that increase in the usage rate of intermodal transportation may provide significant benefits for all of the company objectives on cost, time and environmental issues. Furthermore, it is also reported that compromise programming technique with crisp goals may produce superior results over the other approaches in terms of cost and environmental objectives. On the other hand, best solutions for total transit time objective can be found by interactive fuzzy goal programming approach under the uncertainty of aspiration levels. Finally, scenario analysis have demonstrated that marine transport cost of other logistics service providers' Ro-Ro vessels, upper bounds on number of block train services, lower bounds on utilization rates of the company-owned Ro-Ro vessels and specific portion of road transportation in outsourcing option are the most influential factors on transportation cost, transit time and environmental objectives.

The remainder of this chapter is organized as follows. In Section 5.2, literature review on planning problems in intermodal transportation with OR and AI based solution methods are given. In Section 5.3, details of the problem with intermodal logistics network representation, modeling assumptions and mathematical model formulation are described. Section 5.4 presents a real-life application for model verification and validation. This section also contains deterministic single objective and fuzzy multi-objective optimization results. Scenario analysis is also carried out for managerial insights at the end of Section 5.4. The chapter conclusions and future research directions are also presented in Section 5.5.

5.2 Related Literature on Intermodal Freight Transportation Planning

An overview of recent articles which were studied multi-mode load planning, route selection, service network design problems and relevant applications in intermodal transportation environments can be summarized as follows: A review and classification of OR models and techniques implemented in intermodal freight transportation research field were presented by Macharis and Bontekoning (2004) by considering the goals/specific decisions of different operators and length of the planning horizon. In other words, they categorized the existing intermodal freight planning problems and related studies according to type of decision makers, i.e., drayage operator, terminal operator, network operator and intermodal operator, and planning hierarchy, i.e., strategic, tactical and operational level problems. Then, Caris et al. (2008) extended this previous review and presented a comprehensive literature survey on planning problems in intermodal freight transportation. Similarly, they also categorized the operation problems in accordance with the type of operators and the decision level which reflects the length of the planning horizon. These operators with different field of interests can be summarized as depicted in Figure 5.2. The relevant classification matrix for intermodal operations problems is also given in Table 5.1.

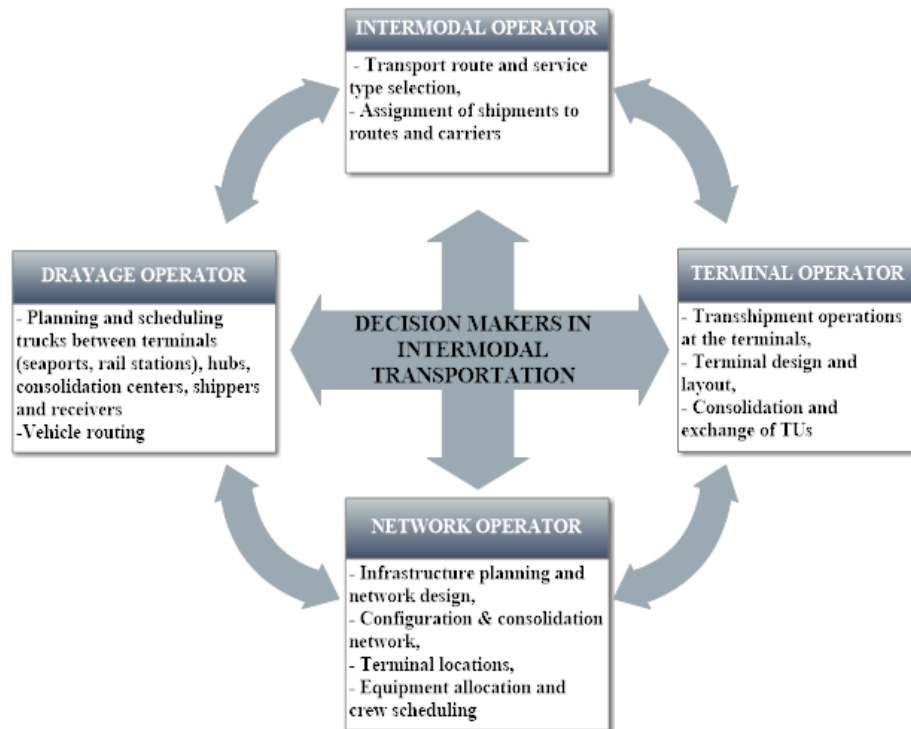


Figure 5.2 Multiple decision makers and their fields of interest in intermodal transportation

Table 5.1 Classification of intermodal operations problems (Macharis & Bontekoning, 2004)

Decision maker	Field of interest	Time horizon		
		Strategic	Tactical	Operational
Drayage operator	-Planning & scheduling of trucks between terminals, shippers and receivers	- Co-operation between drayage companies (central planning), -Truck, trailer and chassis fleet size	-Assignment of shippers and receiver locations to terminals, -Pricing strategies	-Repositioning of trailer chassis and load units, -Scheduling of truck trips, -Vehicle routing
Terminal operator	-Transshipment operations	-Terminal design and layout, -Consolidation and exchange of load units	-Capacity levels of equipment & labor, -Redesign of operational routines and layout structures	-Reschedule capacity based on real-time data, -Allocation of capacity to jobs & job scheduling, -Resource allocation
Network operator	-Infrastructure planning & network design	-Determining the terminal locations, -Infrastructure configuration, -Network design	-Configuration consolidation network, -Determine service types, -Determine production model type, -Allocation of equipment to routes, -Optimal price and level of service	-Scheduling of services, -Load order of trains and barges, -Redistribution of railcars, trailers, barges and load units -Assignment of trailers/containers to flatcars, -Crew scheduling
Intermodal operator	-Route selection for shipments	N.A.	N.A.	-Route and service selection, -Assignment of shipments to routes and carriers, -Routing and repositioning

It was also emphasized by Caris et al. (2008) that there is a scarcity of studies which cover various time horizons and integrate decisions of more than one decision maker. Moreover, these decision makers should work with a high level of coordination so as to run the intermodal transportation system smoothly and improve the efficiency of transport flows. In the literature survey of Caris et al. (2013), intermodal transportation research area is classified as followings: policy support, terminal design, intermodal service network design, intermodal routing, drayage operations and information/communication technology innovations. An integer programming model which purposes to minimize total cost of empty container movements was developed by Choong et al. (2002) to examine the impact of planning horizon length on mode selection and empty container management in intermodal transportation. According to experimental results of a case study in the Mississippi river basin, usage of slower modes of transport, i.e., barge, will increase and empty container distribution plan will become more suitable in case of longer planning periods. A binary integer program was presented by Arnold et al. (2004) for multimodal terminal location problem in a rail/road intermodal transportation system based on a multi-commodity fixed-charge network design model. A heuristic procedure depending upon shortest path algorithms was used to solve large scaled real-world problems within a reasonable computational time. Finally, they investigated the effects of transshipment costs at terminals, locating

new terminals and optimizing current terminal locations under different scenarios. The intermodal routing problem which minimizes cost and travel time was formulated as a multi-objective, multimodal, multi-commodity network flow problem by Chang (2008) considering time windows and non-convex piecewise linear cost functions. Since the NP-hard nature of the problem, a heuristic solution approach based on Lagrangian relaxation and decomposition techniques was proposed to separate the original problem into smaller sub-problems. Shortest path algorithms were utilized to solve sub-problems which correspond to bounded knapsack and incapacitated minimum cost flow problems. Finally, Lagrangian multiplier problem was solved via sub-gradient optimization technique by incorporating a re-optimization method to obtain feasible solutions which do not violate bundle capacity constraints of the original problem. A collaborative planning approach was developed by Puettmann and Stadtler (2010) for decentralized planning of an intermodal transport chain including three autonomous service providers, namely an intermodal operator and two carriers who undertake the drayage activities in regions of shipper and receiver. In detail, they proposed a coordination scheme in which decisions of these service providers are made by iterative proposal generation mechanism depending on three different mathematical programs. These models mainly depend upon multi-commodity network flow and generalized assignment problems. In order to evaluate the cost savings from coordination under demand uncertainty, a heuristic method was also presented to decrease the dimension of scenario tree and solution time.

An integer linear programming formulation was presented by Bauer et al. (2010) for an intermodal scheduled service network design problem including fleet management issues under a central control assumption. They focused on the energy consumption by all of the intermodal transport activities to minimize greenhouse gas emissions. A time-space network representation of the problem was carried out to display the terminals and their links with a recurring planning horizon. The computational experiments were compared to identify trade-off among time-related and environmental goals. Verma and Verter (2010) proposed a bi-objective analytical framework to specify the most appropriate freight shipment plan for regular and hazardous materials in a rail/truck intermodal transportation network. The truck route and train service selection decisions were driven by customer specified lead times

while optimizing the transport cost and public transport risk. An iterative solution procedure which decomposes the main problem into two sub-problems for intermodal train service operations and time-constrained drayage activities was introduced. The cost-risk trade-off analysis was performed by changing the objective weights into a multi-objective method based on linear combinations. An intermodal network optimization model was developed by Yang et al. (2011) in order to achieve the best routing from China to Indian Ocean. They also analyzed effects of the possible new route options on competitiveness of available routes under different virtual cases. Moreover, an integrated cost and goal programming models were utilized so as to handle conflicting objectives in an aggregated manner i.e., minimize cost, transit time and transit time variability. Thus, on-time delivery, reduced inventory/insurance costs were provided without stock-outs while determining the freight routings.

A decision support framework which contains three core models was developed by Macharis et al. (2011) for economic and environmental policy making in intermodal transportation. In detail, this framework involve a multimodal freight transportation model for optimal location of new terminals, a discrete event simulation model for analyzing the potential market area based on market prices and final model for investigating the influence of new intermodal barge terminal on the network characteristics such as average waiting times at locks, turnaround times of terminals, handling time, capacity utilization of waterway network etc. A mixed-integer programming model was proposed by Bierwirth et al. (2012) for tactical planning problem of an intermodal transportation network in Eastern Europe. Their model incorporates service type selection (door-to-door, less-than-train load, full-train-load), mode choice, intermodal terminal selection, freight consolidation for rail transport services and company's production plan etc. The freight consolidation effect and realistic scalable cost functions which reflect the economies of scale were also included within the model. Meisel et al. (2013) extended the integrated production and intermodal freight transportation planning model of Bierwirth et al. (2012) by adding multiple type of commodity, production setups, master production schedule, inventory management, multiple time periods and multi-stage rail transportation services. Moreover, they focused on multiple objectives: minimize total cost of production/transportation and minimize rate of demand distributed by door-to-door

service as an environmental goal. Due to NP-hard nature of the problem, Branch-and-Cut method and two different decomposition-based heuristics were utilized as exact and approximate solution approaches, respectively. Finally, ε -constraint method was employed to handle multiple objectives simultaneously and generate Pareto-optimal solutions. Three different integer programming models which targeted maximization of the train utilization and minimization of the transportation cost were developed by Bruns and Knust (2012) for a load planning problem of trains at an intermodal container terminal. In contrast to the available literature, additional weight restrictions were also taken into account by the developed models besides the length constraints while setting of all wagons of a train and assigning the load units to the slots on the wagons. Actually, these models may differ from each other because of using different modeling characteristics into the weight constraints such as discrete or continuous weight distributions, numbers of type-weight lines etc. The performances of the models were tested based on real-life load planning problem instances in European road-rail terminals.

Cho et al. (2012) formulated a multi-objective multimodal routing problem with time windows based on a weighted constrained shortest path model. Then, Label setting procedure which is a member of dynamic programming algorithms was applied to obtain Pareto optimal solutions by taking into account the trade-off between transportation cost and time. In order to improve performance of this exact transport algorithm, pruning rules were also used to eliminate some paths while seeking for optimal import and export freight routings of cargo containers from Busan to Rotterdam. Thereafter, Pareto optimal solutions are generated and evaluated by using a mathematical model and a multi-attribute decision making method for selecting the most appropriate one among them. A bi-criteria optimization model with transport cost and risk objectives was developed by Verma et al. (2012) for rail-truck intermodal transportation routing problem of hazardous materials. They aimed at determining the most efficient shipment plan for both hazardous materials and regular freights on an intermodal transportation network with multiple transshipment terminals. For the solution of the mathematical model and derivation of non-dominated solutions, a Taboo search based solution approach was proposed and compared with a constructive heuristic, i.e., Greedy algorithm, in terms of both cost and risk associated with

hazardous materials. Assadipour et al. (2015) extended the study of Verma et al. (2012) by incorporating the congestion at the terminals and terminal equipment capacity decisions into the bi-objective non-linear mixed-integer programming model. In other words, the effects of terminal congestion and equipment capacity choices on the intermodal routing decisions were investigated in a rail/road logistics network. A multi-objective genetic algorithm based solution methodology with a non-binary solution representation was also developed to solve the problem due to the non-linear terms into the risk objective function and some constraints. It was also highlighted that delivery time, waiting time and equipment fleet size are the most influential factors that affect the congestion risk at the intermodal terminals.

A multi-objective chance constrained programming model was presented by Kalinina et al. (2013) with stochastic transport times for real time matching of freights and intermodal transport alternatives. They utilized ε -constraint technique to generate Pareto optimal solutions while minimizing the cost, transport time and CO₂ emission objectives jointly. Their proposed model was applied on a real-life case study of a Swedish shipping company with the help of a web-based portal for online transport matching system. A hybrid approach which combines OR and AI techniques was introduced by Garcia et al. (2013) for a container-based specific intermodal transportation problem of a Spanish logistics company. In detail, original problem was first separated into two sub-problems and then solved by a two-step approach. Firstly, three different assignment problems for containers to trucks, trucks and containers to transport routes and trucks to intermodal nodes were solved by both linear programming and a greedy search strategy. Subsequently, automated planning was used to achieve the best transportation mode or path selection for different pick-up and delivery requests of each service.

An integrated intermodal freight transport system which includes short-term traffic flow forecasting analysis and arc flow based mixed-integer programming model was proposed by Bhattacharya et al. (2014) for a rail/road intermodal network optimization. The system implementation was carried out for a real world fast moving consumer goods supply chain network in India. In order to achieve the traffic congestion degree along with different transport routes, a data mining process which

considers both space and time dimensions of the vehicle data was applied. Then, the calculated congestion index was utilized within the proposed spatio-temporal intermodal network optimization model to handle trade-off between operational costs and costs related to time delays for producing effective intermodal scheduling plans. SteadieSeifi et al. (2014) presented an overview of multimodal transportation literature including recent theoretical developments and practical efforts. They mentioned that there are relatively few papers on operational intermodal planning problems over the strategic and tactical level problems. Additionally, it was also emphasized that there is no paper dealt with the dynamic positioning/repositioning of multi-asset resources in intermodal transportation systems into the current literature.

The efficiency of using an intermodal transportation system composed of pipeline, barge, rail and truck were evaluated by Kazemi and Szmerekovsky (2015) when designing a multi-echelon, multi-product and multi-mode downstream petroleum supply chain network. They proved that number, location and capacity of the distribution centers may change in accordance with the transportation mode selection decisions. In addition, it was also indicated that incorporation of the multimodal transportation decisions into the strategic/tactical supply chain planning procedures can provide cost-efficient network configuration and enhance supply chain performance measures. Resat and Turkay (2015) developed a novel bi-objective mixed-integer linear programming model for intermodal transportation network design and operation problem by taking into account the traffic congestion on routes. In order to produce a set of Pareto efficient solutions for the conflicting transport cost and delivery time objectives, augmented ε -constraint method was utilized. Based on a real-life application in Marmara region of Turkey, it was shown that transportation safety can be increased by reducing the traffic congestion and designing a more balanced intermodal logistics network.

Demir et al. (2015) formulated a multi-objective probabilistic mixed-integer linear program for a green intermodal service network design problem including routing plans. They dealt with the uncertainty related to travel times and as well as transport demands by chance-constrained stochastic programming approach. The sample average approximation algorithm was implemented in order to provide robust

transportation plans with respect to transport cost, service/travel time and greenhouse gas targets. An intermodal logistics network design model with a hybrid network topology was developed by Ezabadi and Vergara (2016) to solve integrated terminal/hub location, transportation mode and route selection problems. When these tactical and operational level problems were integrated with the strategic intermodal network design, a path-based composite variable formulation of the problem was carried out. In order to obtain exact solutions of the large scaled problem instances within a reasonable computation time, a two-stage optimization approach was utilized by decomposing the original problem into master and multiple sub-problems. The consolidation effects on total transport cost and travel times were also examined by considering constant discount and delay factors.

Febbraro et al. (2016) introduced a new agent-based modeling framework for short and medium term planning problems in intermodal freight transportation systems. Actually, they proposed a decentralized optimization procedure for cooperative planning of multi-actor systems in order to achieve minimum cost and maximal reliability in intermodal transport chains. The system dynamics were modeled by means of discrete event system simulation and freight delivery plans were generated on a rolling horizon basis. In an effort to share the necessary information among these actors and provide coordination, network communication coordinator was used based on Lagrangian relaxation method. In fact, this method was utilized to solve the complex optimization models for loading/unloading rail-truck terminal operations and transportation operations for optimal routing of containers by trucks or trains. The results of the proposed cooperative planning framework were verified on a case study and compared with first-come-first-served dispatching rule.

5.3 Problem Setting and Mathematical Model Proposal

In this section, a new mixed integer programming model is formulated for a multi-objective, multi-mode and multi-period load planning or intermodal freight transportation planning problem by considering import and export transportation operations simultaneously. The proposed model has a dynamic nature since it takes into account the variability embedded into the import/export transport demands for trailer/container load movements. According the some criteria such as transit time,

tonnage limitations and product characteristics etc., an international logistics company provides various transportation models and services to its customers including direct road freight transport, combined marine and road transport and intermodal transportation. In direct road freight transport, the loads are transferred from origin seaports in Turkey to the consolidation centers of the company via highways and delivery again from these centers to the final destinations within the order countries. Similarly, importation of the loads is begin with the transportation of these loads to the consolidation centers via highways from all over Europe for further transportation and then deliver to the relevant seaports in Turkey. The combined marine and road transport integrates two different transportation modes and serves as an alternative for particularly high tonnage products since the tonnage limitations imposed in European highways. Firstly, the loads are transferred from the origin seaports in Turkey to the seaports in Europe by Ro-Ro vessels and then delivered from these ports to the relevant destinations via highways. Finally, intermodal is a transportation model wherein three distinct means of transport is utilized, i.e., maritime, railway and road transports. Intermodal transportation aims at transferring loads from one location to another in a most effective, punctual, affordable and environment-friendly manner. In intermodal transportation, trailers or containers arriving by Ro-Ro vessels are loaded to block trains at the seaports in Europe and then transferred to rail stations and finally delivered to order countries by road freight transport. A featured intermodal transportation service provides lots of advantages to the company such as timely delivery, cost-effectiveness and environmental awareness. The configuration of intermodal logistics network for the examined multi-mode load planning problem can be portrayed as in Figure 5.3. At seaports or railway stations, block trains and company-owned Ro-Ro vessels arrive and depart in accordance with a fixed time schedule. In addition to the block train and Ro-Ro schedules, configuration of the intermodal transport network is also supposed to be fixed. The intermediate transshipments are also possible for both marine and rail transportation services based on the consolidation concept. In detail, some loads can be unloaded from the Ro-Ro vessel at a transshipment seaport in marine transport and then send to an order country via road transport. Similarly, some extra loads can be loaded to the Ro-Ro vessel at a transshipment seaport and then transferred to origin seaports in Turkey by Ro-Ro vessels.

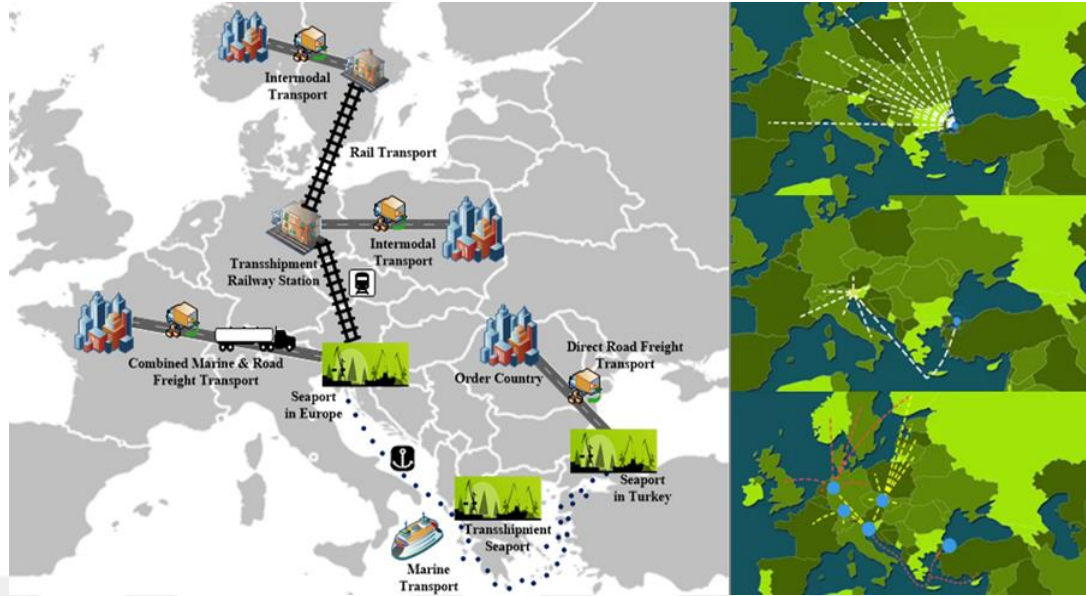


Figure 5.3 Schematic depiction of the intermodal logistics network configuration

In other words, intermediate stops may exist in marine transportation. Moreover, some loads can also be exchanged between the railway stations which correspond to the rail-rail exchange. In fact, some of the trailers can be unloaded from a block train at a transshipment railway station and loaded to a public train on the different rail line. The remaining trailers are delivered to order countries via road freight transport. On the other hand, exchange operations may increase the transit time and total transport costs of the intermodal transportation system. For this reason, they should be performed rapidly and efficiently. In the light of foregoing, the load plan can be constructed by solving the developed mixed-integer programming model to determine:

- Effective mode selection and periodic load allocation to different transport services,
- Composition of direct road freight transport, combined marine and road transport, intermodal transportation, importation and exportation of loads by outsourcing option,
- Marine transportation amounts shipped by company-owned Ro-Ro vessels and other logistics service providers' maritime services,
- The required number of cruises by company-owned Ro-Ro vessels at each month,
- Utilization rate of company-owned Ro-Ro vessels on different marine links,

- The required number of chartered block trains in the directions of both import/export,
- The rail transport amounts transferred by public train services,
- Load transfer amounts at transshipment seaports and railway stations.

The proposed model also incorporates decisions on frequency of company-owned Ro-Ro vessel and block train services. The objective is to find the least costly, less time consuming and environmental friendly load plans on the intermodal transportation network as shown by Figure 5.4.

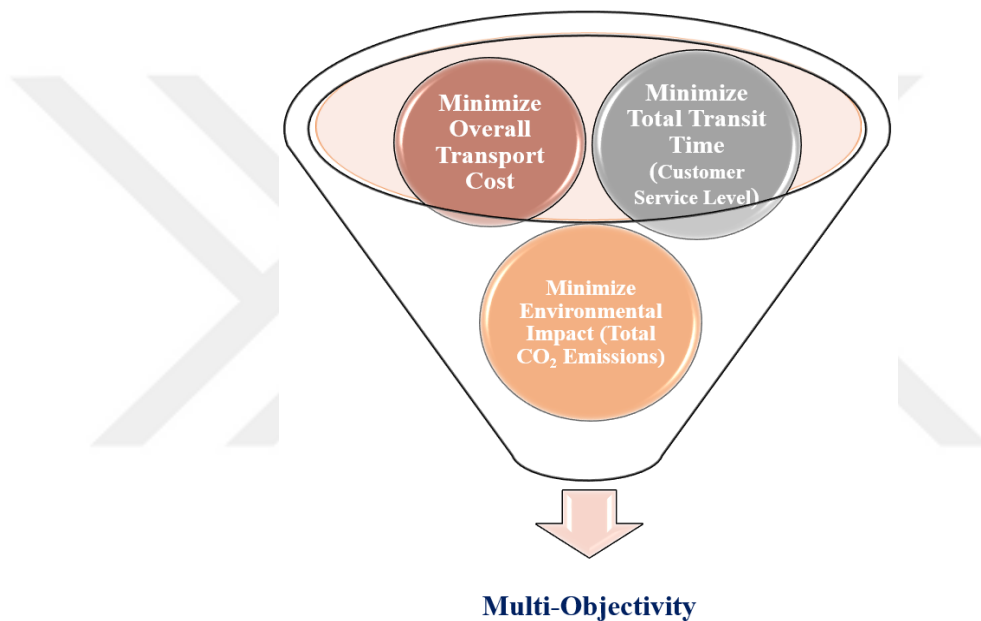


Figure 5.4 Multi-objective nature of the proposed multi-mode load planning model

The proposed load planning model is developed based on the following situations and assumptions. Indeed, these assumptions are made by company experts working at intermodal freight transportation department based on some agreements on tariffs, working conditions, contracts with logistics service providers, customs clearance, railroad freight rates etc.

- For both importation and exportation operations, the domestic distribution services of the logistics company within Turkey are not taken into account by the proposed model. In other words, pre/end haulages in Turkey are not considered.

- It is not allowed for delayed or deferred customer transport demands. All of the monthly demands of the order countries should be satisfied within the relevant time period.
- In maritime logistics, there is no capacity limitation on the quantity of transportation units (trailer or container) shipped by other logistics service providers' Ro-Ro vessels.
- Outsourcing option has an unlimited transportation capacity. This option covers direct road freight transport and combined marine and road transport services.
- In rail transportation system, in contrast to the block trains with fixed time schedules, there is no limitation on the quantity of load units transferred by the public train services.
- Less than Truck load (LTL) is not permitted in the direct road freight transportation.
- Additional shipments can be loaded/unloaded at the transshipment seaports by only the company owned Ro-Ro vessels during the maritime transportation operations.
- It is supposed that monthly import and export transport demands of the order countries are exactly known and considered as deterministic parameters.
- In Trieste seaport, importation and exportation operations can be carried out from/to Istanbul origin seaport by both of the company owned and other logistics service providers' Ro-Ro vessels. On the other hand, trailers or containers can only be transferred by the other logistics service providers between Trieste seaport and other origin seaports in Turkey, i.e., Izmir and Mersin seaports.
- For Sete seaport, transportation operations can be performed from/to Izmir origin seaport by only the company-owned Ro-Ro vessels. In fact, any import or export shipment cannot be performed by the other logistics service providers for this seaport.
- For the import/export operations at a transshipment seaport, i.e., Lavrion seaport, additional shipments can be loaded/unloaded at this seaport during the logistics service. Actually, this transshipment point is only connected with the

marine link between Trieste and Istanbul seaports. In other words, some freights can be loaded or unloaded at this seaport at any time of the transportation service between Trieste and Istanbul seaports in order to satisfy customer demands in the environs of Lavrion seaport.

- The company cannot organize any maritime logistics service with its own Ro-Ro vessels between Istanbul and Toulon seaports. The shipments can be transferred by only the other logistics service providers' Ro-Ro vessels. Currently, it is not possible to organize any maritime service by the company owned Ro-Ro vessels to Toulon seaport from any origin seaport in Turkey.
- For the rail transportation, railway connections are just available from/to Trieste seaport in Europe. In detail, there are direct railway connections between Trieste seaport and some other railway terminals such as Ostrava, Munich, Ludwigshafen and Cologne. Actually, the rail transport operations between these terminals and Trieste seaport can only be achieved by chartering a whole block train with a fixed time schedule.
- However, any rail transport operations cannot be performed by the block trains between Trieste seaport and Munich rail station. Alternatively, there are only public train services available between this seaport and rail station.
- Furthermore, Cologne station is a transshipment point on the railway network of Europe. In fact, some of the shipments can be loaded or unloaded at this rail station and can be transferred by road freight transport so as to satisfy the transport demands in the surrounding order countries. The remaining loads are transferred to Malmö and Gothenburg rail stations by using public train services which have flexible time schedules. Unfortunately, it is not possible to charter block trains between Malmö and Gothenburg rail stations and Cologne transshipment station.

According to these explanations, a multi-objective, multi-mode, multi-period load planning model with simultaneous import/export operations can be formulated through the following equations by using the indices, sets, parameters and decision variables that are introduced in Appendices A1, A2 and A3. The first objective of the proposed model is to minimize total costs of the overall intermodal transportation network which consists of marine transport costs per transportation unit by the company owned or

other logistics service providers' Ro-Ro vessels, rail transport costs per block train service, rail transport costs per transportation unit by the public trains, outsourcing costs and road freight transportation cost of each transportation unit per kilometer (for loaded truck movements only).

(I) Objective-1: Minimize the overall transport costs throughout the intermodal logistics network:

$$\begin{aligned}
\text{Minimize } Z_{Cost} = & \sum_{(i,j) \notin L_{ij}} \sum_{t \in T} R_{ijt}^{exp} \cdot Co_{ij}^{exp} + \sum_{(j,i) \notin L_{ji}} \sum_{t \in T} R_{jit}^{imp} \cdot Co_{ji}^{imp} + \\
& \sum_{(i,j) \notin C_{ij}} \sum_{t \in T} P_{ijt}^{exp} \cdot Cp_{ij}^{exp} + \sum_{(j,i) \notin C_{ji}} \sum_{t \in T} P_{jit}^{imp} \cdot Cp_{ji}^{imp} + \sum_{(j,k) \notin L_{jk}} \sum_{t \in T} S_{jkt}^{exp} \cdot Cb_{jk}^{exp} + \\
& \sum_{(k,j) \notin L_{kj}} \sum_{t \in T} S_{kjt}^{imp} \cdot Cb_{kj}^{imp} + \sum_{(j,k) \notin C_{jk}} \sum_{t \in T} P_{jkt}^{exp} \cdot Cp_{jk}^{exp} + \sum_{(k,j) \notin C_{kj}} \sum_{t \in T} P_{kjt}^{imp} \cdot Cp_{kj}^{imp} + \\
& \sum_{k' \in T_k} \sum_{k'' \in G_k} \sum_{t \in T} P_{k'k''t}^{imp} \cdot Cp_{k'k''}^{imp} + \sum_{k' \in T_k} \sum_{k'' \in G_k} \sum_{t \in T} P_{k'k''t}^{exp} \cdot Cp_{k'k''}^{exp} + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ijlt}^{exp} \cdot d_{jl}^r \cdot Cr + \quad (5.1) \\
& \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ijlt}^{imp} \cdot d_{lj}^r \cdot Cr + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} Z_{ijklt}^{exp} \cdot d_{kl}^r \cdot Cr + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} Z_{ijklt}^{imp} \cdot d_{lk}^r \cdot Cr + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k'' \in G_k} \sum_{l \in G_l} \sum_{t \in T} Z_{ijk''lt}^{exp} \cdot d_{k''l}^r \cdot Cr + \sum_{i \in I} \sum_{j \in J} \sum_{k'' \in G_k} \sum_{l \in G_l} \sum_{t \in T} Z_{ijk''lt}^{imp} \cdot d_{lk''}^r \cdot Cr + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{ilt}^{exp} \cdot d_{il}^r \cdot Cr \\
& + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{ilt}^{imp} \cdot d_{li}^r \cdot Cr + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{ilt}^{exp} \cdot SC_{ilt}^{exp} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{ilt}^{imp} \cdot SC_{ilt}^{imp}
\end{aligned}$$

The second objective which can be associated with the customer service level is to minimize the total transit times related to road, marine and rail transportation services. The transit time also includes loading/unloading times, travel times, times of consolidation operations at the transshipment points, customs clearance times and awaiting times at the seaports and rail stations. This objective contributes to on time delivery of loads to the destinations and satisfaction of customer transport demands as soon as possible. In addition to the road, marine and rail transit time calculations, the transfer times of the loads by the outsourcing option should also be needed. In this context, it is assumed that a specified large portion of the loads which are allocated to outsourcing option is shipped by direct road freight transport and the remaining loads are transferred by combined marine and road freight transport.

(II) Objective-2: Minimize the total transit time or maximize customer service level:

$$\begin{aligned}
\text{Minimize } Z_{\text{Transit-time}} = & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{ilt}^{\text{exp}} \cdot T_{il}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{lit}^{\text{imp}} \cdot T_{li}^r + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ijlt}^{\text{exp}} \cdot (T_{ij}^m + T_{jl}^r) + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ljit}^{\text{imp}} \cdot (T_{lj}^r + T_{ji}^m) + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k \notin G_k} \sum_{l \in L} \sum_{t \in T} Z_{ijklt}^{\text{exp}} \cdot (T_{ij}^m + T_{jk}^t + T_{kl}^r) + \sum_{i \in I} \sum_{j \in J} \sum_{k \notin G_k} \sum_{l \in L} \sum_{t \in T} Z_{lkjit}^{\text{imp}} \cdot (T_{lk}^r + T_{kj}^t + T_{ji}^m) + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{l \in G_l} \sum_{t \in T} Z_{ijk^*lt}^{\text{exp}} \cdot (T_{ij}^m + T_{jk'}^t + T_{k'l}^r + T_{k^*l}^r) + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{l \in G_l} \sum_{t \in T} Z_{lk^*jit}^{\text{imp}} \cdot (T_{lk^*}^r + T_{k^*k'}^t + T_{k'j}^t + T_{ji}^m) + \\
& \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{ilt}^{\text{exp}} \cdot \left[\varphi^{\text{Out}} \cdot T_{il}^r + (1 - \varphi^{\text{Out}}) \cdot \sum_{j \in J} T_{ij}^m + T_{jl}^r \right] + \\
& \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{lit}^{\text{imp}} \cdot \left[\varphi^{\text{Out}} \cdot T_{li}^r + (1 - \varphi^{\text{Out}}) \cdot \sum_{j \in J} T_{lj}^r + T_{ji}^m \right]
\end{aligned} \tag{5.2}$$

For the last objective, the company aims at reducing the mileage on road with its intermodal logistics system and minimizes carbon dioxide, hydrocarbon, particle and nitrogen emissions. The usage of intermodal transportation directs the majority of freights to maritime and railway transports from the usual heavy lifter, road freight transport. The CO₂ emission calculations are performed based on the transportation mode, marine and land route distances and transported loads. In order to compute the savings in CO₂ emitted by different transportation modes, the emission figures of trucks compliant with Euro 5 standards are executed (EKOL, 2016).

(III) Objective-3: Minimize the total CO₂ emissions by different transportation modes:

$$\begin{aligned}
\text{Minimize } Z_{\text{CO}_2} = & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{ilt}^{\text{exp}} \cdot d_{il}^r \cdot CO_2^R + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{lit}^{\text{imp}} \cdot d_{li}^r \cdot CO_2^R + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ijlt}^{\text{exp}} \cdot d_{jl}^r \cdot CO_2^R + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ljit}^{\text{imp}} \cdot d_{lj}^r \cdot CO_2^R + \sum_{i \in I} \sum_{j \in J} \sum_{k \notin G_k} \sum_{l \in L} \sum_{t \in T} Z_{ijklt}^{\text{exp}} \cdot d_{kl}^r \cdot CO_2^R + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{l \in G_l} \sum_{t \in T} Z_{ijk^*lt}^{\text{exp}} \cdot d_{k^*l}^r \cdot CO_2^R + \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{l \in L} \sum_{t \in T} Z_{lk^*jit}^{\text{imp}} \cdot d_{lk^*}^r \cdot CO_2^R + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{l \in G_l} \sum_{t \in T} Z_{lk^*jit}^{\text{imp}} \cdot d_{lk^*}^r \cdot CO_2^R + \sum_{(i,j) \notin L_{ij}} \sum_{t \in T} R_{ijt}^{\text{exp}} \cdot d_{ij}^m \cdot CO_2^M + \sum_{(j,i) \notin L_{ji}} \sum_{t \in T} R_{jit}^{\text{imp}} \cdot d_{ji}^m \cdot CO_2^M + \\
& \sum_{(i,j) \notin C_{ij}} \sum_{t \in T} P_{ijt}^{\text{exp}} \cdot d_{ij}^m \cdot CO_2^M + \sum_{(j,i) \notin C_{ji}} \sum_{t \in T} P_{jit}^{\text{imp}} \cdot d_{ji}^m \cdot CO_2^M + \sum_{k' \in T_k} \sum_{k^* \in G_k} \sum_{t \in T} P_{k^*k't}^{\text{imp}} \cdot d_{k^*k'}^t \cdot CO_2^T +
\end{aligned} \tag{5.3}$$

$$\begin{aligned}
& \sum_{(j,k) \notin L_{jk}} \sum_{t \in T} S_{jkt}^{exp} \cdot Cap_{jk}^{exp} \cdot d_{jk}^t \cdot CO_2^T + \sum_{(k,j) \notin L_{kj}} \sum_{t \in T} S_{kjt}^{imp} \cdot Cap_{kj}^{imp} \cdot d_{kj}^t \cdot CO_2^T + \\
& \sum_{(j,k) \notin C_{jk}} \sum_{t \in T} P_{jkt}^{exp} \cdot d_{jk}^t \cdot CO_2^T + \sum_{(k,j) \notin C_{kj}} \sum_{t \in T} P_{kjt}^{imp} \cdot d_{kj}^t \cdot CO_2^T + \sum_{k' \in T_k} \sum_{k^* \in G_k} \sum_{t \in T} P_{k'k^*t}^{exp} \cdot d_{k'k^*}^t \cdot CO_2^T + \\
& \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{ilt}^{exp} \cdot \left[\varphi^{out} \cdot d_{il}^r \cdot CO_2^R + (1 - \varphi^{out}) \cdot \sum_{j \in J} d_{ij}^m \cdot CO_2^M + d_{jl}^r \cdot CO_2^R \right] + \\
& \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{lit}^{imp} \cdot \left[\varphi^{out} \cdot d_{li}^r \cdot CO_2^R + (1 - \varphi^{out}) \cdot \sum_{j \in J} d_{ij}^r \cdot CO_2^R + d_{ji}^m \cdot CO_2^M \right]
\end{aligned}$$

The constraints of the proposed mixed-integer programming model for an intermodal freight transportation or multi-mode load planning problem can be expressed by the following Equations (5.4) to (5.43):

- i. *Periodic load allocation to different modes of transport in order to satisfy transport demands of order countries by different transportation services:*

$$X_{ilt}^{exp} + \sum_{j \in J} Y_{ijlt}^{exp} + \sum_{j \in D_j} \sum_{k \in K} Z_{ijklt}^{exp} + O_{ilt}^{exp} = De_{ilt}^{exp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (5.4)$$

$$X_{lit}^{imp} + \sum_{j \in J} Y_{ljit}^{imp} + \sum_{j \in D_j} \sum_{k \in K} Z_{lkjit}^{imp} + O_{lit}^{imp} = De_{lit}^{imp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (5.5)$$

- ii. *The specific constraints on marine transportation services:*

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq N_{ij^*t}^{exp} \cdot Cap_{ij^*}^{exp} - \sum_{l \in L} Y_{ij^*lt}^{exp} - \sum_{l \in L} \sum_{k \in K} Z_{ij^*klt}^{exp} \quad \forall (i, j) \in C_{ij} \wedge j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (5.6)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq N_{j^*it}^{imp} \cdot Cap_{j^*i}^{imp} - \sum_{l \in L} Y_{lj^*it}^{imp} - \sum_{l \in L} \sum_{k \in K} Z_{lkj^*it}^{imp} \quad \forall (j, i) \in C_{ji} \wedge j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (5.7)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq N_{ijt}^{exp} \cdot Cap_{ij}^{exp} \quad \forall (i, j) \in C_{ij} \wedge j \notin D_j, \forall t \in T \quad (5.8)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq N_{jit}^{imp} \cdot Cap_{ji}^{imp} \quad \forall (j, i) \in C_{ji} \wedge j \notin D_j, \forall t \in T \quad (5.9)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq N_{ijt}^{exp} \cdot Cap_{ij}^{exp} + P_{ijt}^{exp} \quad \forall (i, j) \in B_{ij} \wedge j \notin D_j, \forall t \in T \quad (5.10)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq N_{jit}^{imp} \cdot Cap_{ji}^{imp} + P_{jit}^{imp} \quad \forall (j, i) \in B_{ji} \wedge j \notin D_j, \forall t \in T \quad (5.11)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} = R_{ijt}^{exp} \quad \{ \forall (i, j) \in C_{ij} \vee B_{ij} \} \wedge \{ j \in T_j \vee j \notin D_j \}, \forall t \in T \quad (5.12)$$

$$\sum_{l \in L} Y_{ljit}^{imp} = R_{jit}^{imp} \quad \{ \forall (j, i) \in C_{ji} \vee B_{ji} \} \wedge \{ j \in T_j \vee j \notin D_j \}, \forall t \in T \quad (5.13)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} + \sum_{k \in K} \sum_{l \in L} Z_{ijklt}^{exp} \leq N_{ijt}^{exp} \cdot Cap_{ij}^{exp} - \sum_{l \in L} Y_{ij'lt}^{exp} + P_{ijt}^{exp} \quad (5.14)$$

$$\forall (i, j) \in C_{ij}, j \in D_j \wedge j \in \gamma_j, j' \in T_j, \forall t \in T$$

$$\sum_{l \in L} Y_{ljit}^{imp} + \sum_{k \in K} \sum_{l \in L} Z_{lkjit}^{imp} \leq N_{jit}^{imp} \cdot Cap_{ji}^{imp} - \sum_{l \in L} Y_{lj'it}^{imp} + P_{jit}^{imp} \quad (5.15)$$

$$\forall (j, i) \in C_{ji}, j \in D_j \wedge j \in \gamma_j, j' \in T_j, \forall t \in T$$

$$\sum_{l \in L} Y_{ijlt}^{exp} + \sum_{k \in K} \sum_{l \in L} Z_{ijklt}^{exp} = R_{ijt}^{exp} + P_{ijt}^{exp} \quad \forall (i, j) \in B_{ij} \vee C_{ij}, j \in D_j, \forall t \in T \quad (5.16)$$

$$\sum_{l \in L} Y_{ljit}^{imp} + \sum_{k \in K} \sum_{l \in L} Z_{lkjit}^{imp} = R_{jit}^{imp} + P_{jit}^{imp} \quad \forall (j, i) \in B_{ji} \vee C_{ji}, j \in D_j, \forall t \in T \quad (5.17)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} + \sum_{k \in K} \sum_{l \in L} Z_{ijklt}^{exp} \leq P_{ijt}^{exp} \quad \forall (i, j) \notin C_{ij}, j \in D_j, \forall t \in T \quad (5.18)$$

$$\sum_{l \in L} Y_{ljit}^{imp} + \sum_{k \in K} \sum_{l \in L} Z_{lkjit}^{imp} \leq P_{jit}^{imp} \quad \forall (j, i) \notin C_{ji}, j \in D_j, \forall t \in T \quad (5.19)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq P_{ijt}^{exp} \quad \forall (i, j) \in L_{ij}, j \notin D_j, \forall t \in T \quad (5.20)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq P_{jit}^{imp} \quad \forall (j, i) \in L_{ji}, j \notin D_j, \forall t \in T \quad (5.21)$$

$$R_{ijt}^{exp} / Cap_{ij}^{exp} = S_{ijt}^{exp} \quad \forall (i, j) \notin L_{ij}, j \notin \gamma_j, \forall t \in T \quad (5.22)$$

$$R_{jit}^{imp} / Cap_{ji}^{imp} = S_{jit}^{imp} \quad \forall (j, i) \notin L_{ji}, j \notin \gamma_j, \forall t \in T \quad (5.23)$$

$$(R_{ijt}^{exp} + R_{ij^*t}^{exp}) / Cap_{ij^*}^{exp} = S_{ij^*t}^{exp} \quad \forall (i, j) \notin L_{ij}, j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (5.24)$$

$$(R_{jit}^{imp} + R_{j^*it}^{imp}) / Cap_{j^*i}^{imp} = S_{j^*it}^{imp} \quad \forall (j, i) \notin L_{ji}, j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (5.25)$$

$$U_{ijt}^{exp} = R_{ijt}^{exp} / (N_{ijt}^{exp} \cdot Cap_{ij}^{exp}) \quad \forall (i, j) \notin L_{ij}, \forall t \in T \quad (5.26)$$

$$U_{jit}^{imp} = R_{jit}^{imp} / (N_{jit}^{imp} \cdot Cap_{ji}^{imp}) \quad \forall (j, i) \notin L_{ji}, \forall t \in T \quad (5.27)$$

$$LB_{ijt}^{exp} \leq U_{ijt}^{exp} \text{ and } LB_{jit}^{imp} \leq U_{jit}^{imp} \quad \forall (i, j) \notin L_{ij}, \forall t \in T, \forall (j, i) \notin L_{ji} \quad (5.28)$$

iii. The specific constraints on railway transportation services:

$$\sum_{i \in I} \sum_{l \in L} Z_{ijklt}^{exp} \leq S_{jkt}^{exp} \cdot Cap_{jk}^{exp} \quad (j, k) \in C_{jk} \setminus \{T_k\}, \forall t \in T \quad (5.29)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lkjit}^{imp} \leq S_{kjt}^{imp} \cdot Cap_{kj}^{imp} \quad (k, j) \in C_{kj} \setminus \{T_k\}, \forall t \in T \quad (5.30)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{ijklt}^{exp} \leq Pt_{jkt}^{exp} \quad (j, k) \in L_{jk}, \forall t \in T \quad (5.31)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lkjlt}^{imp} \leq Pt_{kjt}^{imp} \quad (k, j) \in L_{kj}, \forall t \in T \quad (5.32)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{ijklt}^{exp} \leq S_{jkt}^{exp} \cdot Cap_{jk}^{exp} + Pt_{jkt}^{exp} \quad (j, k) \in B_{jk} \setminus \{T_k\}, \forall t \in T \quad (5.33)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lkjlt}^{imp} \leq S_{kjt}^{imp} \cdot Cap_{kj}^{imp} + Pt_{kjt}^{imp} \quad (k, j) \in B_{kj} \setminus \{T_k\}, \forall t \in T \quad (5.34)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{ijk'lt}^{exp} + \sum_{i \in I} \sum_{l \in G_l} \sum_{k^* \in G_k} Z_{ijk^*lt}^{exp} \leq S_{jk't}^{exp} \cdot Cap_{jk'}^{exp} \quad (5.35)$$

$$\forall j \in D_j, \forall k' \in T_k \cap (j, k') \in C_{jk'}, \forall t \in T \quad (5.36)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lk'jit}^{imp} + \sum_{i \in I} \sum_{l \in G_l} \sum_{k^* \in G_k} Z_{lk^*jit}^{imp} \leq S_{k'jt}^{imp} \cdot Cap_{k'j}^{imp} \quad (5.37)$$

$$\forall j \in D_j, \forall k' \in T_k \cap (k', j) \in C_{k'j}, \forall t \in T \quad (5.38)$$

$$\sum_{i \in I} \sum_{j \in D_j} \sum_{l \in G_l} Z_{ijk^*lt}^{exp} \leq Pt_{k'k^*t}^{exp} \quad \forall k' \in T_k, \forall k^* \in G_k \cap (k', k^*) \in L_{k'k^*}, \forall t \in T \quad (5.39)$$

$$\sum_{i \in I} \sum_{j \in D_j} \sum_{l \in G_l} Z_{lk^*jit}^{imp} \leq Pt_{k^*k't}^{imp} \quad \forall k' \in T_k, \forall k \in G_k \cap (k^*, k') \in L_{k^*k'}, \forall t \in T \quad (5.40)$$

$$LB_{jkt}^{exp} \leq S_{jkt}^{exp} \leq UB_{jkt}^{exp} \text{ \& } LB_{kjt}^{imp} \leq S_{kjt}^{imp} \leq UB_{kjt}^{imp} \quad \forall (k, j) \notin L_{kj}, \forall (j, k) \notin L_{jk}, \forall t \in T \quad (5.41)$$

$$|S_{jkt}^{exp} - S_{kjt}^{imp}| \leq 1 \quad \forall (k, j) \notin L_{kj}, \forall (j, k) \notin L_{jk}, \forall t \in T \quad (5.42)$$

$$\left| \sum_{t \in T} (S_{jkt}^{exp} - S_{kjt}^{imp}) \right| \leq 1 \quad \forall (k, j) \notin L_{kj}, \forall (j, k) \notin L_{jk} \quad (5.43)$$

iv. *Non-negativity and integrality restrictions of decision variables:*

$$0 \leq U_{ijt}^{imp} \leq 1 \text{ and } 0 \leq U_{jit}^{exp} \leq 1 \quad \forall (i, j) \notin L_{ij}, \forall (j, i) \notin L_{ji}, \forall t \in T \quad (5.44)$$

$$X_{ilt}^{imp}, X_{lit}^{exp}, Y_{ijlt}^{imp}, Y_{ljit}^{exp}, Z_{ijklt}^{imp}, Z_{lkjlt}^{exp}, O_{ilt}^{imp}, O_{lit}^{exp}, Y_{ij^*it}^{imp}, Y_{ij^*lt}^{exp}, Z_{lkj^*it}^{imp}, Z_{ij^*klt}^{exp}, R_{jit}^{imp}, R_{ijt}^{exp}, \quad (5.45)$$

$$Y_{lj^*it}^{imp}, Y_{ij^*lt}^{exp}, S_{k'jt}^{imp}, S_{jk't}^{exp}, P_{ijt}^{imp}, P_{jit}^{exp}, Pt_{jkt}^{imp}, Pt_{kjt}^{exp}, S_{jkt}^{imp}, S_{kjt}^{exp}, Pt_{k^*k't}^{imp}, Pt_{k'k^*t}^{exp} \geq 0 \text{ integer} \quad (5.46)$$

Constraints (5.4) and (5.5) maintain that import and export transport demands of each order country have to be satisfied in each month through the different transportation services, i.e., direct road freight transport, combined marine and road transport, intermodal transportation and outsourcing option. According to constraints (5.6) and (5.7), transportation capacity of the company owned Ro-Ro vessels should be sufficient for both importation and exportation between the origin and destination

seaports. In other words, these constraints represent the capacity restrictions on load units that can be shipped by only the company owned Ro-Ro vessels on the specific marine links. It should also be noted here that the seaport which represents the origin or destination of the import/export transport operation has not any railway connection with a rail station. In detail, the only alternative is the road freight transport after/before the marine transport service. Actually, these constraints are also valid for the transshipment seaports, i.e., Lavrion port, without any railway connection. Similarly, constraints (5.8) and (5.9) are also the capacity restrictions for the marine transport services which can only be performed by the company-owned Ro-Ro vessels and where the seaports, i.e., Sete port, have no railway connection. Actually, these are the capacity limitations and balance equations for the marine links which have main seaports and transshipment seaports in Europe. Additionally, these marine capacity constraints may differentiate based on the railway connection of the seaports and the type of the utilized Ro-Ro vessels. For instance, marine transport services can only be performed by the company-owned Ro-Ro vessels for the transshipment seaports. The constraints (5.10) and (5.11) are formulated for the marine transport operations which can be conducted by both company-owned and other logistics service providers' Ro-Ro vessels. Similar to constraints (5.6) - (5.9), it is assumed that the seaports have not any railway connection with a rail station for these marine transport operations. By the constraint sets (5.12) and (5.13), one can calculate the total amounts of load units transferred by only the company owned Ro-Ro vessels from/to the transshipment marine seaports or the other seaports which have no railway connection. Actually, these constraints are the balance equations for the seaports, i.e., Lavrion and Sete ports. Constraints (5.14) and (5.15) are also capacity restrictions for the seaports where importation and exportation operations can be performed by both company owned and other logistics service providers' Ro-Ro vessels. In contrast to the previously formulated constraints (5.6) - (5.13), it should be noted here that origin or destination seaport is directly connected with a railway station. Moreover, it is also supposed that the marine links related to the main seaport, i.e. Trieste port, also incorporates at least one transshipment seaport such as Lavrion port. In detail, this port is just a transshipment point between the specified main seaports, i.e., Istanbul and Trieste ports. For this reason, the additional shipments loaded/unloaded at this transshipment

seaport should also be considered within the capacity of the company owned Ro-Ro vessels which operate between these origin and destination seaports. Similar to the constraints (5.12) and (5.13), one can calculate the amounts of load units delivered by both company-owned and other logistics service providers' Ro-Ro vessels from/to the seaports which are directly connected with a railway station based on the constraint sets (5.16) and (5.17). In fact, these constraints correspond to the balance equations for the seaports, i.e. Trieste, that connected with some railway stations such as Ludwigshafen, Cologne, Munich, and Ostrava. By making use of the constraints (5.18) and (5.19), quantities of the import and export shipments in marine transportation which are performed by only the other logistics service providers' Ro-Ro vessels can be computed. It is obvious that there should be a railway connection between the associated seaports, i.e., Izmir-Trieste ports, Mersin-Trieste ports and the railway stations. Similarly, constraints (5.20) and (5.21) are also formulated for the marine transportation services which can only be performed by the other logistics service providers' Ro-Ro vessels by excluding railway connections, i.e., Istanbul – Toulon. Based on the constraints (5.22) and (5.23), the number of cruises that have to be carried out by the company owned Ro-Ro vessels on each marine link can be calculated. However, these constraints are only valid for the main seaports, i.e., Izmir-Sete ports which do not contain any transshipment seaport in Europe. Moreover, the decision variables related to these cruises are defined as real numbers since the loads of the other logistics companies can also be transported by the company's Ro-Ro vessels. Thus, the specific percentage of company's loads on each marine link at each time period can also be determined by making use of these continuous variables. In a similar way, the number of import/export cruises by the company-owned Ro-Ro vessels which also involve the transport operations from/to transshipment seaports can be calculated by the constraint sets (5.24) and (5.25). Additionally, the utilization rates of the company owned Ro-Ro vessels on each marine link at each month can be determined by means of the constraints (5.26) and (5.27). In detail, the capacity utilization rates are just for the company's loads which are only transported by its own Ro-Ro vessels. These rates can be computed by dividing the total number of monthly load units shipped by the company-owned Ro-Ro vessels into the multiplication of maximum number of monthly cruises and the capacity of a Ro-Ro vessel. Since some agreements

on marine tariffs and weekly fixed schedules, there are lower and upper bounds available on these utilization rates. These bounds can be expressed by the constraint set (5.28). Constraints (5.29) and (5.30) are the capacity restrictions on the load units that can be shipped by only the block trains on the railway network, i.e., Trieste-Ostrava, Trieste-Ludwigshafen. In constraints (5.31) and (5.32), quantities of the import and export load units that can only be transferred by the public trains on the railway network can be acquired, i.e., Trieste-Munich. Similarly, capacity limitations are formulated in constraints (5.33) and (5.34) for the rail stations where export/import transportation operations can be performed by both block train and public train services. In all of the constraint set (5.29) to (5.34), transshipment rail stations, i.e., Cologne station, are excluded while handling these capacity limitations since this type of station is connected with some other rail stations instead of a seaport such as Trieste port. In other words, constraints (5.35) and (5.36) represent capacity limitations on the import/export transportation operations for the transshipment rail station which corresponds to a hub on the railway network and located among the specified main rail stations i.e., Trieste - Malmö, Trieste - Gothenburg. In fact, some of the load units which arrive to Cologne transshipment station by the block trains can be distributed to the surrounding order countries via road freight transport. Then, the remaining ones can be transferred to the other order countries via public trains. It should be emphasized here that transportation operations between a transshipment rail station and its connected seaports have to be performed by using only the block trains. In other words, public train services are not available for these transportation operations between this type of rail station and relevant seaport, i.e., Cologne station and Trieste port. On the other hand, transportation operations between this transshipment rail station and the some other stations, i.e. Gothenburg and Malmö, can only be performed by using the public trains as formulated in constraints (5.37) and (5.38). Constraint (5.39) presents the monthly lower and upper bounds on the rail lines where only the block trains services are available. Based on the previous experiences and expert opinions, difference between the number of import and export block train services on each rail line at each month may be at most one. Actually, there should be a balance between the railway services in the directions of import and export transportation operations in each time period. In detail, the difference between import and export

railway services of a specific block train can be realized at most one within a monthly time limit. These constraints are resulted from the monthly scheduling limitations and can be formulated as in Equation (5.40). This balance is also valid for annual basis and can be reflected by the constraint (5.41). Finally, constraint (5.42) defines lower and upper bounds on the decision variables related to the capacity utilization rates of the company-owned Ro-Ro vessels and constraint (5.43) preserves the non-negativity of decision variables and maintains that some of these variables must take integer values.

5.4 Real-Life Application in a Large-Sized International Logistics Company

5.4.1 Data Description and Deterministic Single Objective Optimization Results

In order to illustrate the usefulness, validity and practicality of the proposed model, a real-life application is presented in a large-sized international logistics company in Turkey. The company is the fastest growing Turkish Logistics Corporation in Europe with over 100.000 m² of own warehouses and 1.200 multinational employees. In addition, it is listed among the pioneering suppliers of integrated logistics services in both Turkey and Europe with its distribution centers with more than 450.000 m² indoor areas in Turkey and a fleet of over 4.000 trucks, trailers and containers. The company provides intermodal services and intercontinental logistics solutions including maritime routes and railways to a substantial majority of the best known global firms and brands all around the world by carrying thousands of containers full of materials, finished products, industrial and consumer goods. Although each sector has different logistics requirements, the company offers customized transportation solutions for various sectors. The turnovers of the company with respect to the different logistics services and sectors can be depicted as in the following Figures 5.5 and 5.6.

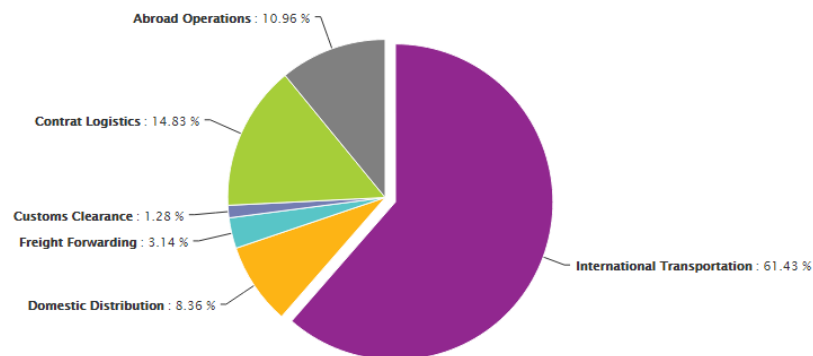


Figure 5.5 The company turnovers with respect to different logistics services (EKOL, 2016)

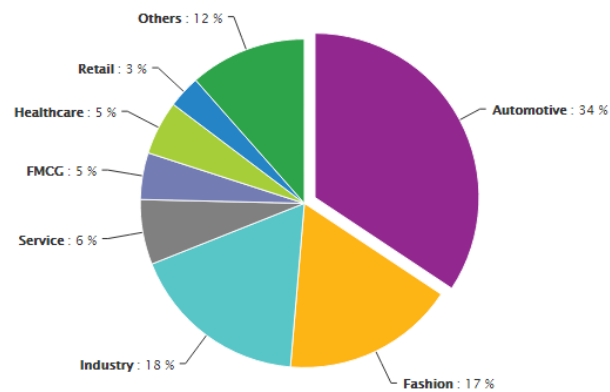


Figure 5.6 The company turnovers with respect to different sectors (EKOL, 2016)

As mentioned previously, the company's intermodal transportation system is based on the shipments of trailers or containers from Istanbul, Izmir and Mersin seaports to the seaports of Trieste or Sete via company owned Ro-Ro vessels. The trailers or containers arriving by the company owned Ro-Ro vessels are loaded to the block trains by the site equipment in the seaport without use of any truck. Arriving trailers and containers are unloaded from the block trains and transported to the Ostrava, Cologne or Ludwigshafen consolidation centers or to the final destination for exportation via road freight transport. In the same manner, the loads are brought via road transport to Ludwigshafen or Cologne stations and consolidated there for transferring to Trieste seaport via railways; and then brought into Turkish origin seaports via the company owned Ro-Ro vessels in case of importation. The configuration of the real life intermodal logistics network can be shown by Figure 5.7.

In the real-life case study, intermodal logistics network is composed of four seaports in Europe with a single transshipment seaport, three origin seaports in Turkey, three railway stations of block trains with a single transshipment railway station and finally three railway stations for only the public train services. There are also forty nine order countries in Europe which correspond to the aggregated customers and need to be satisfied both import/export transport demands from/to Turkey. The planning horizon is set to one year and composed of twelve monthly periods. Before presenting the used data, structure of the examined real-life intermodal logistics network should be given.



Figure 5.7 Intermodal logistics network configuration of the real life case study (EKOL, 2016)

Tables 5.2 and 5.3 present the marine and railway logistics network structures or the subsets of marine and railway links in terms of the proposed model formulation.

Table 5.2 Logistics network subsets related to the maritime transportation

From/To	Istanbul			Izmir			Mersin			T_j	D_j	γ_j
	L_{ij}	C_{ij}	B_{ij}	L_{ij}	C_{ij}	B_{ij}	L_{ij}	C_{ij}	B_{ij}			
Trieste			⊗	⊗			⊗				⊗	⊗
Lavrio		⊗								⊗		
Sete					⊗							
Toulon	⊗											

Table 5.3 Railway line structure

From/To	Trieste			T_k	D_k	G_k
	L_{kj}	C_{kj}	B_{kj}			
Ostrava		⊗			⊗	
Munich	⊗				⊗	
Ludwigshafen		⊗			⊗	
Cologne		⊗		⊗	⊗	
Malmö	⊗					⊗
Gothenburg	⊗					⊗

Thus, the proposed model is reclaimed based on the following information gained from the intermodal freight transportation department of the company: 3 round trips per week take place between Istanbul origin seaport and Trieste port and a single round trip between Izmir and Sete ports. Each trip's duration is 60 hours and trips are realized with company owned Ro-Ro vessels which are equipped with state-of-the-art technology and each have a capacity of 249 mega-trailer or 45ft container. Each

weekday, the company runs block trains between Istanbul and Europe with approximately transit time of 6 days. Hence, it can save many liters of diesel fuels and reduce carbon dioxide emissions compared to the vehicle consumptions in road freight transportation. The transportation capacity of a block train is defined as 32 trailers or containers per train service and minimal 8 train services should be performed on each rail link at each month. The CO₂ emission values are computed on kilometer basis as 0.918 kg/km for road freight transportation including a trailer with 23.800 kg load capacity. Furthermore, an average value of 0.357 kg/km is provided from IFEU Ecological Transport Information Tool (IFEU EcoTransIT) for marine CO₂ emissions. Finally, since the electrical trains, usually used in Europe, are slow in terms of average speed, the CO₂ emission value is taken as 0.05 kg/km. The intervals of the other parameter values used in the real-life case study are given in Table 5.4.

Table 5.4 Data ranges used in the case study

Parameters	Range of values
Monthly import load demands of the order countries (TU/Month)	0 - 370
Monthly export load demands of the order countries (TU/Month)	0 - 366
Marine transport cost by the company owned Ro/Ro vessels (€/TU)	500 - 1475
Transportation capacity of the company owned Ro/Ro vessels (TU)	165 - 240
Marine transport cost by the other logistics service providers (€/TU)	647,73 – 918,3
The rail cost of per block train service (€/Train service)	20121 - 23328
Transportation capacity of the block trains (TU)	28 - 32
Rail transport cost by the public trains (€/TU)	685
Road freight transport cost per kilometer (€ TU/km)	1,20
Maximum cruise numbers by the company owned Ro/Ro vessels per month	4 - 14
Maximum train services by the block trains per month	12 - 41
The road distance between seaports in Turkey and order countries (km)	540 - 5070
The road transit time between seaports in Turkey and order countries (hr)	27 - 254
The road distance between seaports in Europe and order countries (km)	50 - 4160
The road transit time between seaports in Europe and order countries (hr)	2.5 - 208
The road distance between rail stations and order countries (km)	50 - 3015
The road transit time between rail stations and order countries (hr)	2.5 – 150,8
The rail transit time between seaports and rail stations in Europe (hr)	20 - 24
The marine transit time between seaports in Turkey and Europe (hr)	17 - 96

When the model is run with these data through optimization software LINGO 15.0 on an Intel Core i7 2 GHz IBM PC for each objective separately, the following deterministic optimization results or independent objective function values are obtained as given in Table 5.5. Actually, this table represents a payoff matrix and can be used as benchmarks to determine the aspiration levels and max-min limits of each goal under uncertainty. In general, decision analysts can estimate the lower and upper limits of these goals based on their knowledge and experience. In addition, these limits can also be determined by using this payoff table which guaranteed the feasibility of

each fuzzy goal in the solution phase. In detail, the main diagonal of the payoff matrix denotes the individual best solutions for each objective. Then, lower and upper bounds can be designated from this payoff matrix in order to be used for the construction of membership functions which represent the satisfaction levels of goals.

Table 5.5 Payoff matrix and summary of the deterministic optimization results

Objective Functions	Total Cost	Total Transit Time	Total CO ₂ Emission
Total Transport Cost (€)	151890560.5	8997322.46	106572584.5
Total Transit Time (hrs.)	164507645.5	8558320.15	108593881.4
Total CO ₂ Emission (kg)	157078215.8	9004663.9	100278315.6
Model Class	MILP		
Total number of variables	35729		
Integer variables	35592		
Total number of constraints	10728		
Total non-zero elements	174022		
Optimality gap (%)	0.0		
Total number of iterations	56107	2686	1370
CPU time (sec.)	94.73	19.18	19.04

Moreover, corresponding optimal usage rates of different transportation modes and outsourcing can be presented as in Figures 5.8 – 5.10 in case of single objective deterministic optimization.

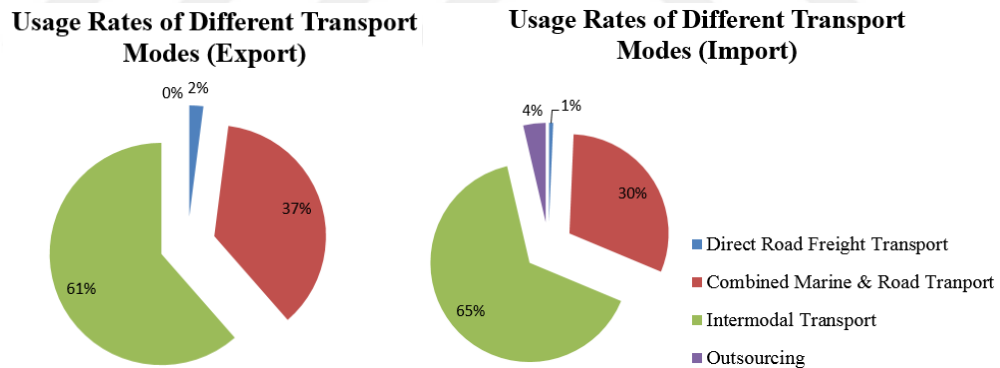


Figure 5.8 Usage rate of different transportation modes and outsourcing: Minimize total transport cost

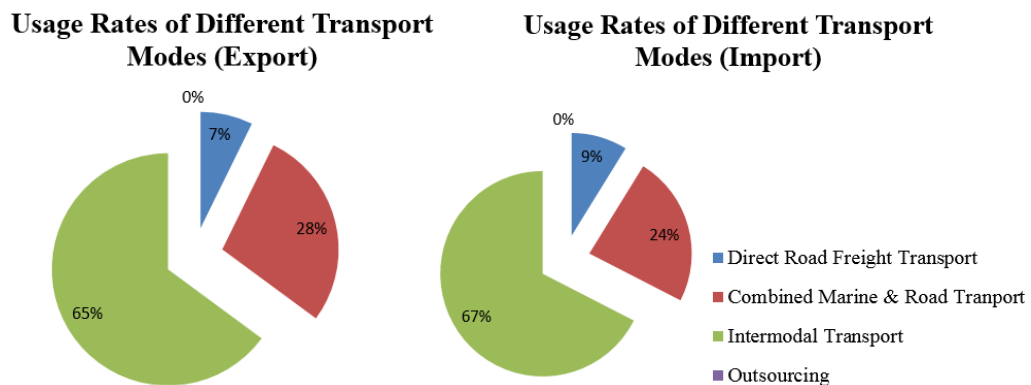
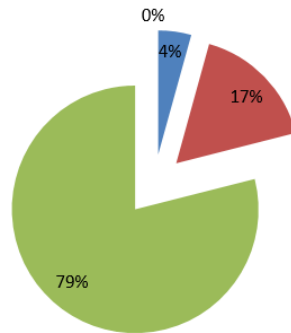


Figure 5.9 Usage rate of different transportation modes and outsourcing: Minimize total transit time

Usage Rates of Different Transport Modes (Export)



Usage Rates of Different Transport Modes (Import)

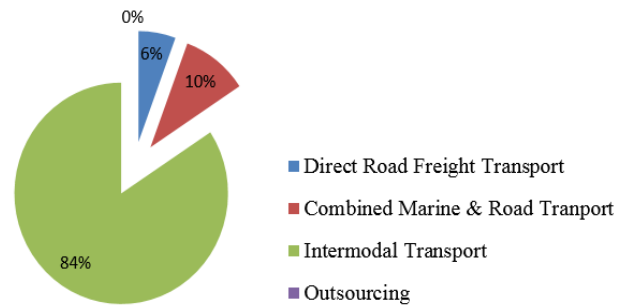


Figure 5.10 Usage rate of different transportation modes & outsourcing: Minimize total CO₂ emission

Actually, these rates are specified both importation and exportation operations in annual basis when the aforementioned objectives are optimized separately. According to the deterministic optimization results, a large portion of the customer transport demands should be met by using intermodal transportation in both directions of importation and exportation. In fact, it is the most preferred transport option for the stated real-life load planning case. It can also be emphasized here that intermodal transportation is the most appropriate way of freighting in terms of economic, customer satisfaction and environmental issues. In other words, intermodal transportation is able to contribute all of these conflicting objectives. On the contrary to cost minimization where the marine transport costs constitutes the large parts of the overall annual transport cost, the amounts of loads shipped by the outsourcing option will increase when the transit time and environmental objectives are optimized. In such a case, the usage rate of combined marine and road freight transport will decrease because of increasing usage of intermodal transportation. Moreover, the usage of direct road freight transport will be relatively high due to its high-level of speed and flexibility in case of transit time minimization. According to Figure 5.11, there is a balance among the monthly transport costs since there is no significant variation on monthly import/export transport demands and total operational costs. The variation of monthly usage rate of outsourcing option for import/export can also be demonstrated as in Figure 5.12 in terms of cost objective. There will be increments in import/export outsourcing shipments in the beginning of the planning horizon. But, the amounts of loads transferred by outsourcing way will decrease towards the end of the year.

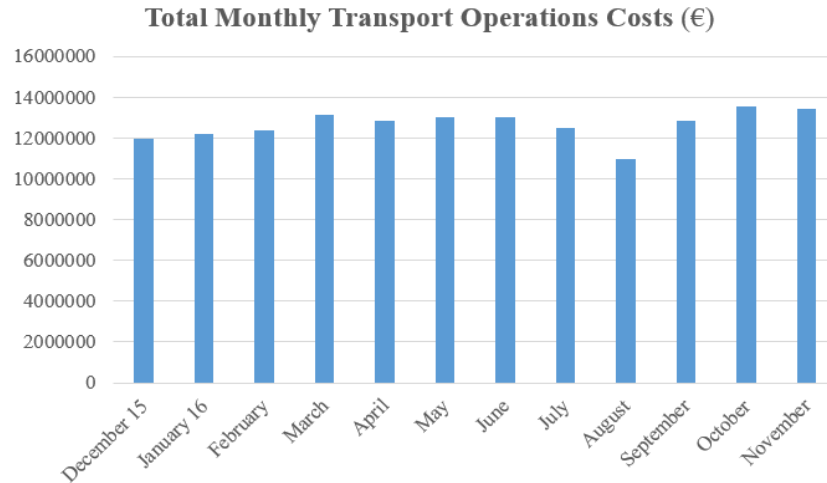


Figure 5.11 The variation of monthly transport costs

Indeed, the imbalance between import and export outsourcing quantities will disappear to the end of the planning period since the increasing usage of intermodal transportation. On the other hand, all of these import and export outsourcing quantities will shift to direct road freight transportation when the total transit time objective is taken into account.

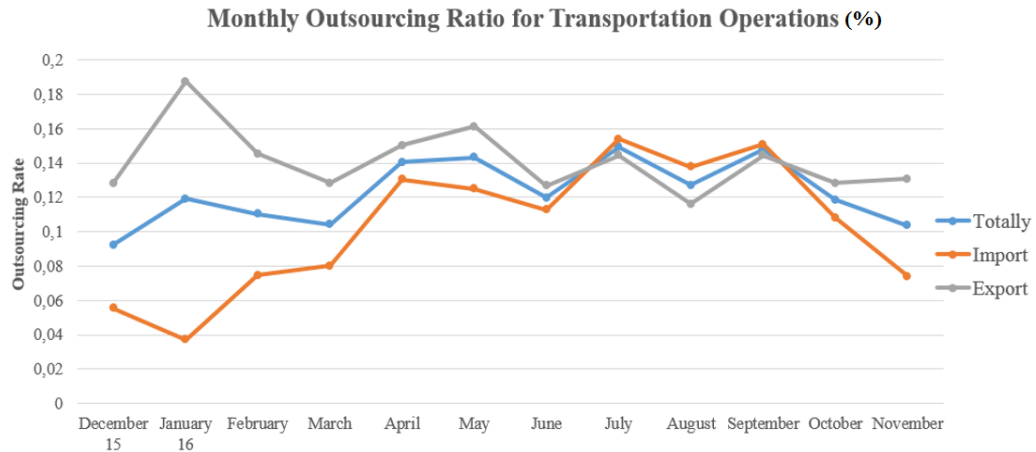


Figure 5.12 The monthly variation of outsourcing ratio for import/export transportation operations

5.4.2 Multi-Objective Optimization Results via Different Approaches under Certain and Uncertain Environments

In order to generate a compromise solution to the decision analyst under crisp and/or uncertain environments, the following multiple objective optimization (MOO) approaches are chosen from the literature and applied to the proposed multi-mode load planning model:

- Compromise programming technique with different distance metrics (CP),
- Fuzzy goal programming approach with different importance and priorities (FGP-DIP),
- Weighted additive fuzzy goal programming approach (WFGP),
- Interactive fuzzy goal programming approach (IFGP).

In the following next sub-sections, detailed explanations will be presented for these MOO approaches.

5.4.2.1 Compromise Programming Approach

In order to solve the proposed multi-objective load planning model under certain environments, compromise programming technique which was first introduced by Zeleny (1973) is applied. Apart from the latter goal programming approaches, this technique does not require any subjective information from the decision analyst. In other words, the decision analyst does not need to release preferences and/or weights about the objectives. Additionally, this technique does not require any information on the target values of the goals and needs relatively smaller number of computational runs since it selects a unique optimal solution from a set of Pareto efficient solutions. For all of these reasons, it is an appropriate multi-objective optimization technique to find compromise solution for the current load planning problem. This technique mainly depends on the choice of a unique solution which is the closest one to the ideal point. The closeness is measured by the following distance function (Gan et al., 1995):

$$d(x, y) = \left(\sum_{g=1}^G |f_g(x) - z_g^*|^p \right)^{1/p} \quad (5.47)$$

where $f_g(x)$; $g = 1, \dots, G$ are real valued objective functions and z_g^* represents the reference or ideal point. The value of parameter, p specifies a particular distance metric. For instance, when $p = 1$, it corresponds to the Pythagorean distance between any given two points. When $p = 2$, it presents the Euclidean distance. Actually, $p = 1$ and $p = \infty$ present the longest and shortest distances between these two points. The most widely generated compromise solutions are for p -values of $p = 1$ and $p = \infty$ because of their linear forms. However, other p values $1 < p < \infty$ need to

solve non-linear programming models (Bilbao-Terol et al., 2006; Baykasoğlu et al., 2016). For example, in the case of $p = 2$, the compromise program will be a quadratic program. Based on all of this information, the corresponding compromise program for the solution of multi-objective load planning model can be formulated as follows:

$$\text{Minimize } (|Z_{Cost} - Z_1^*|^p + |Z_{Transit-time} - Z_2^*|^p + |Z_{CO2} - Z_3^*|^p)^{1/p} \quad (5.48)$$

In order to reach the compromise solution, following linear and non-linear (quadratic) compromise programs are solved via LINGO 15.0 optimization software. Before solving these compromise programs, reference or ideal points should be found since this technique aims to minimize total distances. To this end, the proposed model is solved for each objective function separately. Then, the following ideal points are achieved $Z_1^* = 1518900560.5$, $Z_2^* = 8558320.15$ and $Z_3^* = 100278315.6$ as also presented in the payoff Table 5.5.

$$\text{Min } Z_C = |Z_{Cost} - Z_1^*| + |Z_{Transit-time} - Z_2^*| + |Z_{CO2} - Z_3^*| \quad p = 1 \quad (5.49)$$

$$\text{Min } Z_C = \sqrt{(Z_{Cost} - Z_1^*)^2 + (Z_{Transit-time} - Z_2^*)^2 + (Z_{CO2} - Z_3^*)^2} \quad p = 2 \quad (5.50)$$

$$\text{Min } Z_C = \text{Max } (|Z_{Cost} - Z_1^*|, |Z_{Transit-time} - Z_2^*|, |Z_{CO2} - Z_3^*|) \quad p = \infty \quad (5.51)$$

Since the objective function of the compromise program with Pythagorean distance metric ($p = 1$) in Equation (5.46) involves summation of the absolute value terms, this non-linear objective function can be linearized as follows (Baker, 2015):

$$\left\{ \begin{array}{l} \text{Minimize } Z_1^+ + Z_1^- + Z_2^+ + Z_2^- + Z_3^+ + Z_3^- \\ Z_{Cost} - Z_1^* + Z_1^+ - Z_1^- = 0 \\ Z_{Transit-time} - Z_2^* + Z_2^+ - Z_2^- = 0 \\ Z_{CO2} - Z_3^* + Z_3^+ - Z_3^- = 0 \\ \text{Constraint Set (4) - (43)} \\ Z_1^+, Z_1^-, Z_2^+, Z_2^-, Z_3^+, Z_3^- \geq 0 \end{array} \right. \quad (5.52)$$

where $Z_1^+, Z_1^-, Z_2^+, Z_2^-, Z_3^+$ and Z_3^- are a pair of auxiliary variables to account for the positive and negative deviations of the previously formulated objective functions. Similarly, due to the usage of max operator for absolute values of the deviations, objective function of the compromise program with Chebyshev distance metric ($p = \infty$) can be linearized as follows (Mangasarian, 2007; Mangasarian, 2013):

$$\left\{ \begin{array}{l} \text{Minimize } \delta \\ Z_{Cost} - Z_1^+ + Z_1^- - Z_1^- = 0 \\ Z_{Transit-time} - Z_2^+ + Z_2^- - Z_2^- = 0 \\ Z_{CO2} - Z_3^+ + Z_3^- - Z_3^- = 0 \\ Z_1^+ + Z_1^- \leq \delta \\ Z_1^+ + Z_1^- \geq \delta - (1 - \theta_1).M \\ Z_2^+ + Z_2^- \leq \delta \\ Z_2^+ + Z_2^- \geq \delta - (1 - \theta_2).M \\ Z_3^+ + Z_3^- \leq \delta \\ Z_3^+ + Z_3^- \geq \delta - (1 - \theta_3).M \\ \theta_1 + \theta_2 + \theta_3 \geq 1 \quad \theta_1, \theta_2 \text{ and } \theta_3 \in \{0,1\} \\ \text{Constraint Set (4) - (43) and } Z_1^+, Z_1^-, Z_2^+, Z_2^-, Z_3^+, Z_3^- \geq 0 \end{array} \right. \quad (5.53)$$

where δ represents an auxiliary variable which is set to the maximum of absolute value of deviations and θ_1, θ_2 and $\theta_3 \in \{0,1\}$ are binary variables used to transform the maximum operator into linear form. Also, M is a huge positive number. Finally, solution of the multi-objective load planning model with deterministic goals is provided by making use of compromise programming technique with different distance metrics as presented in Table 5.10. Moreover, CP approach presents the following usage rates of different transportation modes for importation, exportation and outsourcing as given by Figures 5.13 – 5.15.

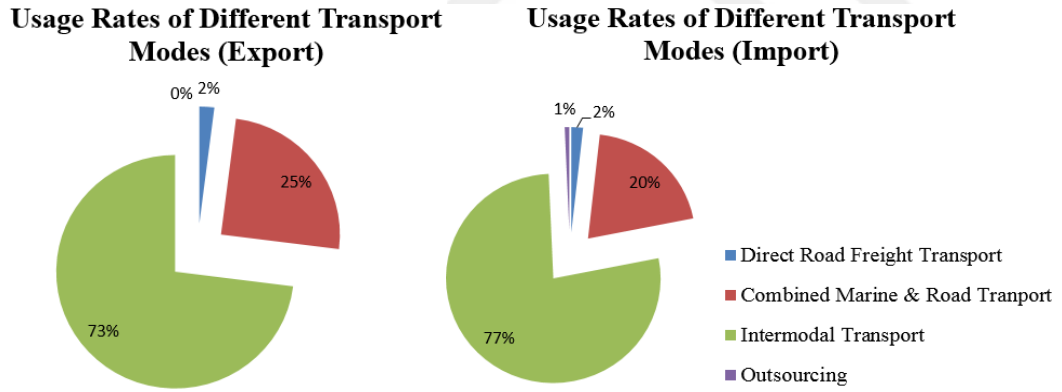
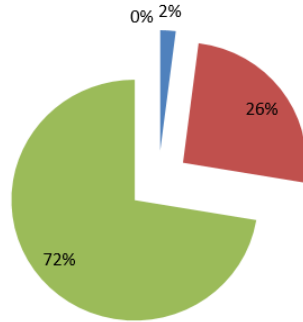


Figure 5.13 Usage rate of transportation modes & outsourcing via CP with Pythagorean distance

The multi-objective computational analysis has shown that similar results can be obtained from the application of CP approach with different distance metrics. It is also obvious that the usage rate of intermodal transportation will increase and rates of road freight transportation and outsourcing will decrease when compared to single objective deterministic optimization results. It should also be noted here that compromise programming approach provided comparatively better results in terms total transport cost over the latter goal programming based approaches as it is seen by Figure 5.24.

Usage Rates of Different Transport Modes (Export)



Usage Rates of Different Transport Modes (Import)

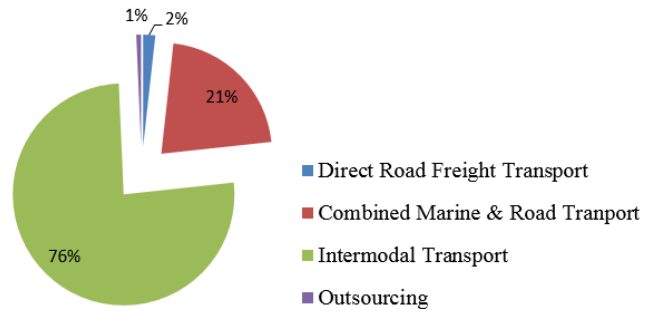
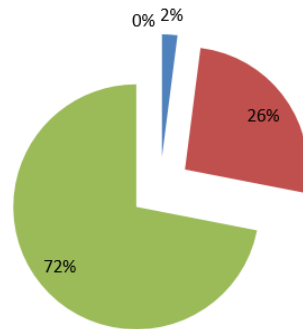


Figure 5.14 Usage rates of transportation modes & outsourcing via CP with Euclidean distance metric

Usage Rates of Different Transport Modes (Export)



Usage Rates of Different Transport Modes (Import)

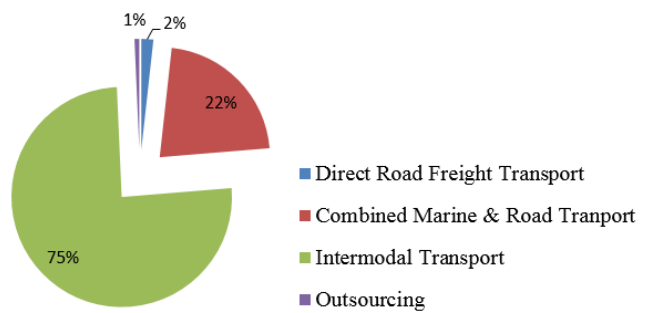


Figure 5.15 Usage rate of transportation modes & outsourcing via CP with Chebyshev distance metric

Furthermore, the best environmental results can also be yielded by compromise programming approach with Pythagorean distance metric as also clearly seen from Figure 5.26. However, satisfactory solutions cannot be yielded by using this approach in terms of customer satisfaction. Because, the generated compromise solutions have relatively larger total transit times than the fuzzy goal programming based approaches. Lastly, it should be emphasized here that uncertainty related to the aspiration levels of the goals are not considered by this approach due to the complex structure of fuzzy distance measures in fuzzy version of the compromise programming approach.

5.4.2.2 Fuzzy Goal Programming Approach with Different Importance & Priorities

The explicit assessment and measurement of the total transport cost, transit time and CO₂ emission objectives are challenging tasks for the decision analyst and require a great deal of human perception. Because, some information may be incomplete or unobtainable for the coefficients into these objective functions. Therefore, objective

values or aspiration levels of these goals may become fuzzy in character and their importance weights, satisfaction sequence or achievement order should be evaluated linguistically. In order to deal with this uncertainty embedded into the aspiration levels of these multiple objectives, Chen and Tsai (2001) proposed a fuzzy goal programming approach by considering different importance and priorities. In detail, they incorporated the different importance and preemptive priority structure into a single formulation by using an additive model. On the other hand, under such a fuzzy environment, determination of a desirable achievement degree related to each goal is a difficult task for the decision analyst. Therefore, the most preferred method is to use linguistic terms/expressions for identifying these desirable achievement degrees imprecisely. The linguistic term can be defined as a variable whose values are words or phrase in natural or artificial language (Jamalnia & Soukhakian, 2009). In this regard, a fuzzy linguistic variable is generally characterized via fuzzy numbers (Chang, 1996). The imprecise or vague nature of the linguistic assessments about the importance of different goals can be characterized by the following triangular fuzzy numbers which are given in Table 5.6.

Table 5.6 Linguistic variables for the importance weights of different goals under uncertainty

Linguistic variables	Triangular fuzzy numbers
Very low important (VLI)	(0,0,%10)
Low important (LI)	(%5,%15,%25)
Somewhat low important (SLI)	(%20,%32.5,%45)
Medium (M)	(%40,%50,%60)
Somewhat high important (SHI)	(%55,%67.5,%80)
High important (HI)	(%75,%85,%95)
Very high important (VHI)	(%90,%100,%100)

Furthermore, membership functions of these linguistic variables which are related to the importance of different fuzzy goals are also depicted in Figure 5.16. In this figure, $\mu_L(\beta)$ represents the membership functions of each linguistic variable, where $\mu_L(\beta) \in [0,1]$ and β display a variable which takes an achievement degree in the interval of $[\beta_{min}, \beta_{max}]$, $0 \leq \beta_{min} \leq \beta_{max} \leq 1$.

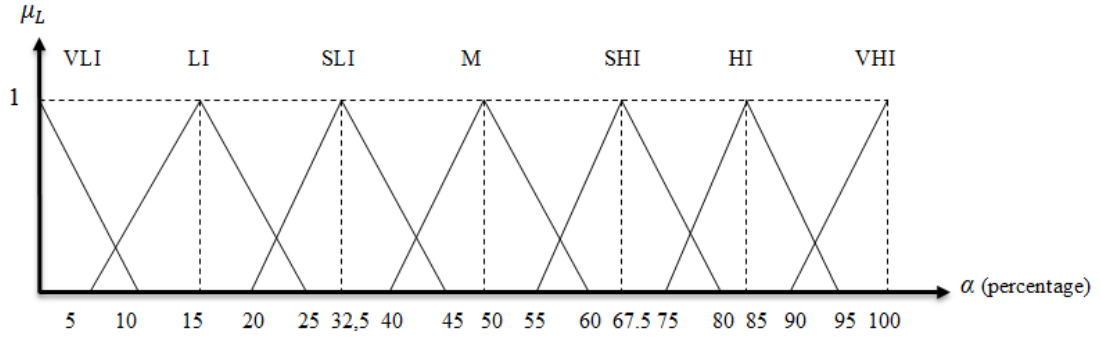


Figure 5.16 Membership functions for the linguistic variables (Jamalnia & Soukhakian, 2009)

In order to calculate the value of desirable achievement degree for each fuzzy goal, Liou and Wang's (1992) defuzzification based ranking method is employed. This method ranks the fuzzy numbers in a group decision making environment where the index of optimism of each group member are different. In this approach, the total integral value $I_T^\beta(\tilde{A})$ of a triangular fuzzy number $\tilde{A} = (a, b, c)$ can be calculated as follows based on the index of optimism, $\beta \in [0,1]$ which reflects the decision maker's optimistic attitude.

$$I_T^\beta(\tilde{A}) = \frac{1}{2} [\beta \cdot c + b + (1 - \beta)a] \quad (5.54)$$

The total integral value represents a pessimistic decision maker when β is equal to "0". Additionally, it is suitable for moderate and optimistic decision makers where the value of β is set to "0.5" and "1.0", respectively. In the light of this information, value of this total integral value, $I_T^\beta(\tilde{A})$ can be used as a desirable achievement degree (θ_{ik}) of k^{th} fuzzy goal for i^{th} decision maker. In this chapter, the linguistic evaluations about the importance of the fuzzy goals are performed by five different experts of the logistics company who have different index of optimisms as shown in Table 5.7. Actually, all of these experts are responsible from quite different intermodal transportation planning activities of the logistics company. After obtaining the linguistic assessment of each fuzzy goal from these company experts, the individual desirable achievement degree of each goal for each expert can be calculated by using the fuzzy ranking approach of Liou and Wang (1992) as presented in Table 5.8.

Table 5.7 Linguistic evaluations of relative importance of fuzzy goals by different company experts

Decision Makers	Drayage Operator	Terminal Operator	Financial Advisor	Network Operator	Intermodal Operator
Index of optimism	Pessimistic	Optimistic	Moderate	Optimistic	Moderate
Total Transport Cost	VHI	M	VHI	SHI	SHI
Total Transit Time	VHI	HI	M	HI	SHI
Total CO2 Emission	M	SLI	SLI	SHI	VHI

In fact, the total integral values of these linguistic variables are computed for each objective function by using Equation (5.51) according to the optimism index of each expert so as to defuzzify the triangular fuzzy numbers associated with the linguistic evaluations. Before calculating the overall priority or aggregated desirable achievement degree of each fuzzy goal, hierarchy between the company experts or importance weights of the group members should be determined.

Table 5.8 Individual desirable achievement degree of each fuzzy goal for each company expert

Decision Makers	Drayage Operator	Terminal Operator	Financial Advisor	Network Operator	Intermodal Operator
Index of optimism	Pessimistic	Optimistic	Moderate	Optimistic	Moderate
Total Transport Cost	0.95	0.55	0.975	0.7375	0.675
Total Transit Time	0.95	0.9	0.5	0.9	0.675
Total CO2 Emission	0.45	0.3875	0.325	0.7375	0.975

Actually, there may not an exact hierarchy among the decision makers in most of the real-life settings. Furthermore, relative importance or hierarchy of group members may change over time and thus this hierarchy may have some sort of ambiguity. For this purpose, the company experts are ranked in a fuzzy way in this study. Then, the relative importance or fuzzy weights of the group members are determined by using a subjective method namely “*Rank Reciprocal*” which is solely based on preference information given by an expert (Malczewski, 1999). After calculation of the reciprocal fuzzy weights of the company experts, they are normalized by using the following normalization procedure for fuzzy numbers (Fenton & Wang, 2006):

$$\tilde{W}_i = \left\{ \left(\frac{w_{i1}}{M}, \frac{w_{i2}}{M}, \frac{w_{i3}}{M} \right) \quad M = \max_i \{w_{i3}\} \right. \quad (5.55)$$

In order to calculate the fuzzy weights of the group members, the hierarchy between the company experts is determined by the board chairman of the logistics company.

In fact, these experts are ranked in fuzzy way as $\tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}$ and $\tilde{5}$ and the fuzzy hierarchy among the group members is depicted by Figure 5.17.

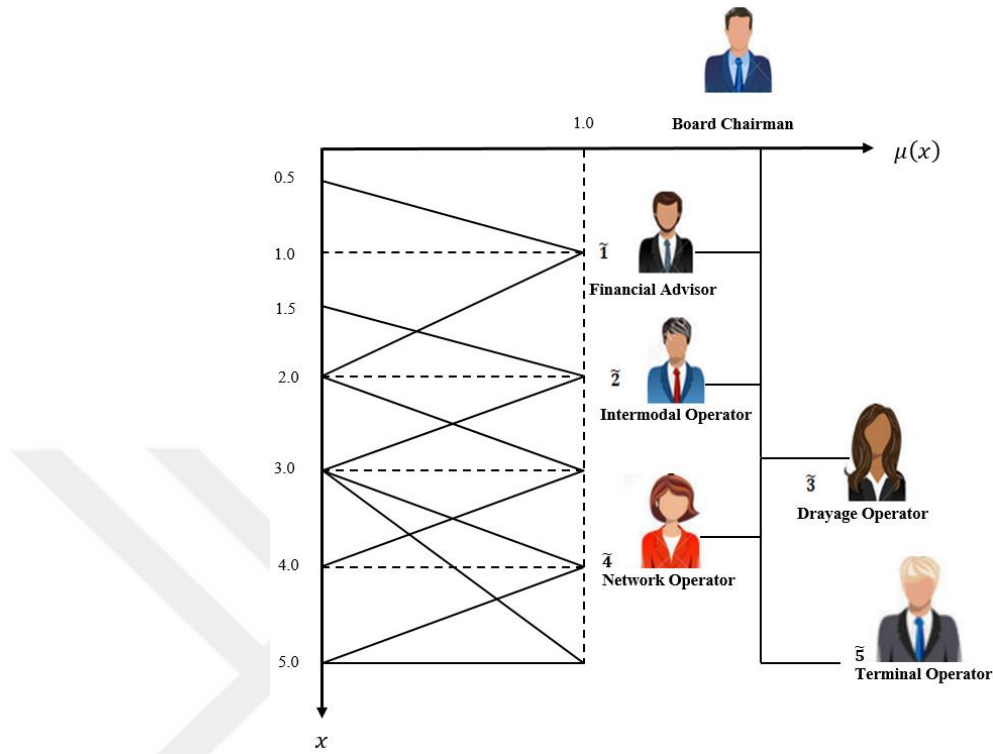


Figure 5.17 Fuzzy hierarchy between the group members in an international logistics company

After assigning the fuzzy ranks and calculating the reciprocal fuzzy weights, normalized importance weights of the company experts can be provided as in Table 5.9. Subsequently, the normalized fuzzy importance weights of the group members are defuzzified by using the fuzzy ranking approach of Liou and Wang (1992) depending upon the index of optimism of the board chairman. In this chapter, it is supposed that the board chairman of the logistics company has a moderate optimistic attitude.

Table 5.9 Determination of importance weights of company experts via rank reciprocal method

Decision Makers	Drayage Operator	Terminal Operator	Financial Advisor	Network Operator	Intermodal Operator
Fuzzy Rank	(2, 3, 4)	(3, 5, 5)	(0.5, 1, 2)	(3, 4, 5)	(1.5, 2, 3)
Reciprocal fuzzy weights	(0.25, 0.33, 0.5)	(0.2, 0.2, 0.33)	(0.5, 1, 2)	(0.2, 0.25, 0.33)	(0.33, 0.5, 0.67)
Normalized fuzzy weights	(0.125, 0.16, 0.25)	(0.1, 0.1, 0.16)	(0.25, 0.5, 1)	(0.1, 0.125, 0.16)	(0.16, 0.25, 0.33)
Defuzzified weights	0.177	0.116	0.563	0.129	0.25

After determining the importance weights of the company experts, the overall priority of each fuzzy goal can be calculated by using the following Equation (5.56) based on the weighted geometric mean of individual desirable achievement degrees (Subulan et al., 2015a):

$$\bar{\theta}_k = \left(\prod_{i=1}^n \theta_{ik}^{w_i} \right)^{1/\sum_{i=1}^n w_i} \quad (5.56)$$

where θ_k is overall priority of the k^{th} fuzzy goal, θ_{ik} is the individual desirable achievement degree of i^{th} decision maker for the k^{th} fuzzy goal and w_i is importance weight of the i^{th} group member. In summary, final desirable achievement degrees are computed as $\bar{\theta}_1 = 0.83$, $\bar{\theta}_2 = 0.653$ and $\bar{\theta}_3 = 0.471$ in a group decision making environment for the total transport cost, transit time and CO₂ emission objectives, respectively. After that, the payoff matrix previously given in Table 5.5 is used to specify the lower and upper limits of each fuzzy goal. To quantify the fuzzy aspiration levels of these goals, linear and continuous membership functions are found to be appropriate. Lastly, membership function of each fuzzy goal and regarding analytical definitions can be constructed by making use of these limits as displayed in Figure 5.18 (Zimmermann, 1976).

The following crisp equivalent model given by Equation (5.57) is formulated via the method of Chen and Tsai (2001) for the stated multi-mode load planning problem with fuzzy goals.

$$\left\{ \begin{array}{l} \text{Maximize } \sum_{k=1}^3 \mu_k = \mu_{Cost} + \mu_{Transit-time} + \mu_{CO2} \\ \mu_{Cost} \leq \frac{Z_1^U - Z_{Cost}}{Z_1^U - Z_1^*} \\ \mu_{Transit-time} \leq \frac{Z_2^U - Z_{Transit-time}}{Z_2^U - Z_2^*} \\ \mu_{CO2} \leq \frac{Z_3^U - Z_{CO2}}{Z_3^U - Z_3^*} \\ \text{Constraint set (4) - (43)} \\ \mu_{Cost} \geq \bar{\theta}_1, \mu_{Transit-time} \geq \bar{\theta}_2 \text{ and } \mu_{CO2} \geq \bar{\theta}_3 \\ 0 \leq \mu_{Cost}, \mu_{Transit-time}, \mu_{CO2} \leq 1 \end{array} \right. \quad (5.57)$$

In the above formulation, Z_k^U represents the upper bounds of the k^{th} objective function which are derived from the payoff matrix. The objective of this crisp LP model is to maximize summation of the achievement degrees of all fuzzy goals in which desirable achievement degrees or overall priorities reflect the relative importance of the goals. Thus, more important goals will have larger achievement degrees. The model constraints ensure that achievement degrees of these fuzzy goals must be at least pre-specified overall priority levels.

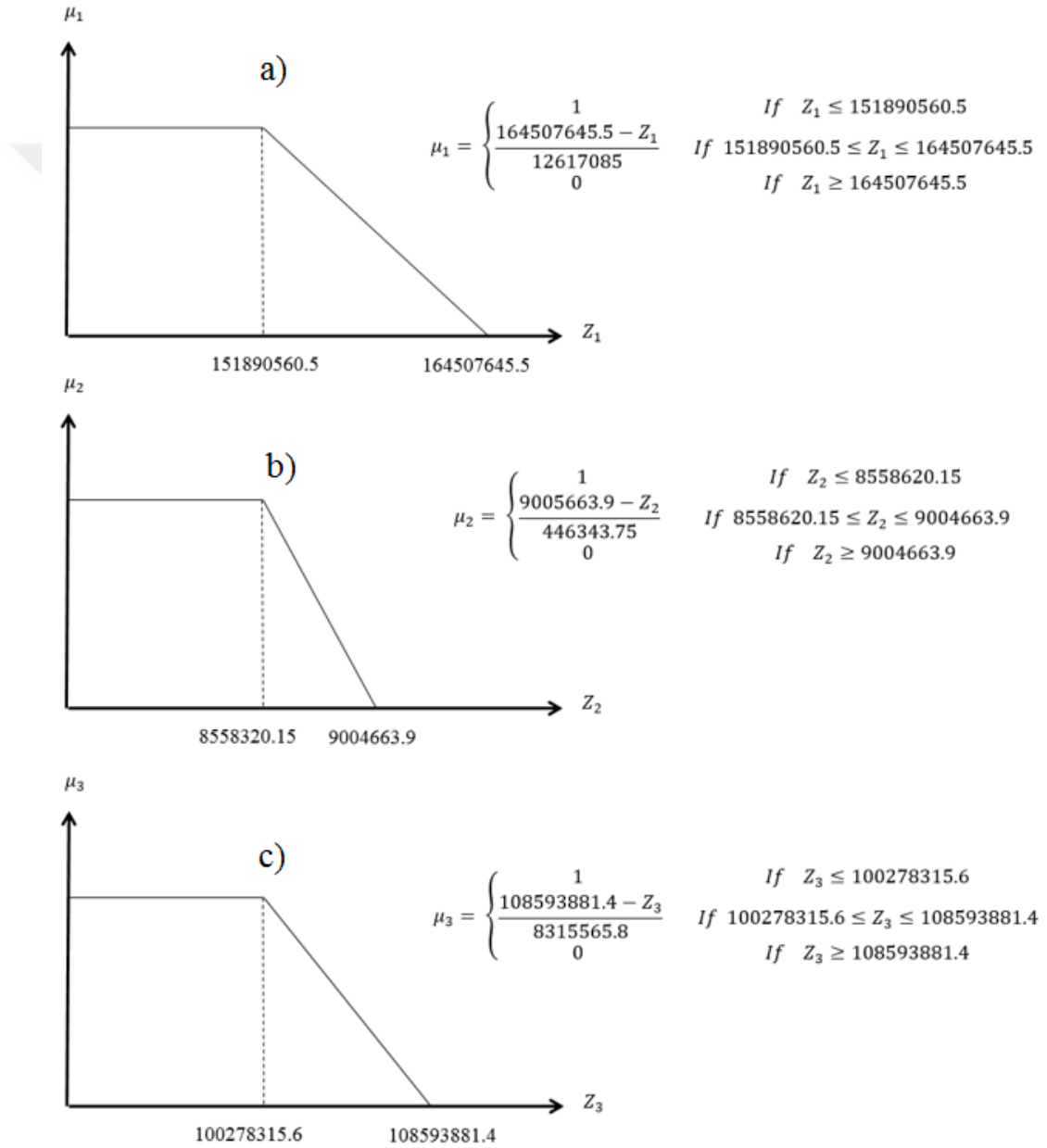


Figure 5.18 Membership functions of fuzzy goals: a) Total transport cost, b) Total transit time, c) Total CO₂ emission

In case of the high level of overall priorities, infeasibility problem may occur in the solution phase. In this situation, membership functions of the fuzzy goals or model parameters may be modified with respect to the company experts' preferences or achievement degrees can be reduced rationally (Chen & Tsai, 2001; Subulan et al., 2015a). As a result, following optimal usage rates of different transportation modes and outsourcing can be obtained as in Figure 5.19 when the FGP-DIP approach of Chen and Tsai (2001) is applied. Although this approach offers satisfactory solutions in terms of cost and transit time objectives, it causes significantly high CO₂ emissions when compared to other MOO approaches.

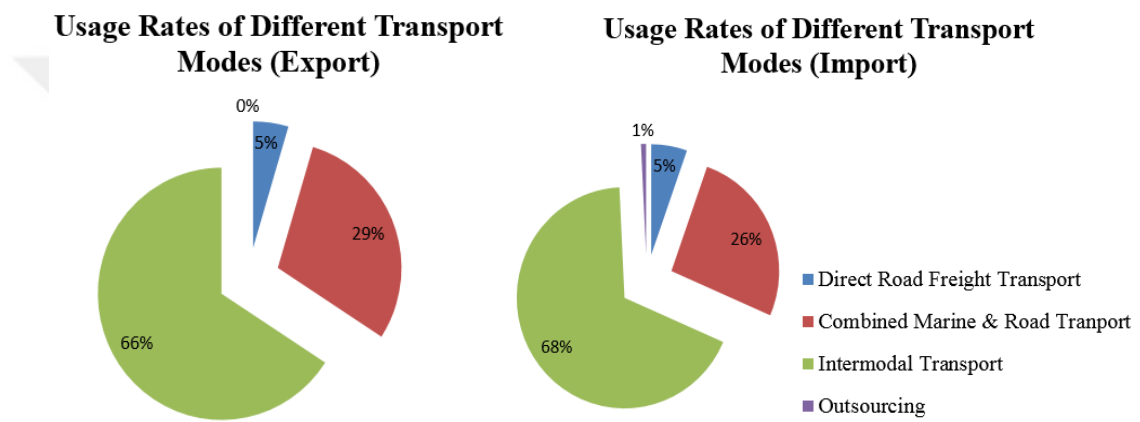


Figure 5.19 Usage rates of different transportation modes and outsourcing via FGP approach with DIP

The computational result of FGP-DIP approach highlights that decreases in usage rate of intermodal transportation and increases in outsourcing ratio will cause not only extra costs and high environmental impact but also provide transit time reduction.

5.4.2.3 A Weighted Additive Fuzzy Goal Programming Approach

One of the most important issues in fuzzy goal programming approaches is the reflection of importance weights of the fuzzy goals since they may generally be different for the decision analyst. For this reason, Tiwari et al. (1987) added the weights of each goal in the objective function as coefficients in order to consider this relative importance. This approach aggregates weighted membership functions of fuzzy goals where these goals have distinct importance degrees. It aims at minimizing the sum of weighted deviation from each fuzzy aspiration level of goals. In detail, a single weighted linear utility function is utilized by this approach to explain the overall

preference of the decision analyst for emerging the relative importance of these goals. This utility function is computed by multiplying the membership function of each fuzzy goal with their associated weights. Then, the obtained results are added together (Amid et al., 2009). After construction of the membership functions of all fuzzy goals (see in Figure 5.18), the weight value should be assigned to each objective according to its priority. The major difficulty of this approach is the appropriate determination of relative importance of each goal by the decision analyst. In order to assess these weights correctly, the desirable achievement degrees or overall priorities which are derived in the previous section is used under fuzzy group decision making environment. Because, the objectives with higher priority levels should have also higher weights. This is because desirable achievement degrees represent the importance degree of each objective to one another. Then, a standardization procedure is implemented on these values to satisfy that summation of the weights must be equal to 1.0. This procedure can be formulated as in Eq. 5.58 to obtain final importance weights:

$$w_k = \bar{\theta}_k / \sum_{k=1}^3 \bar{\theta}_k \quad (5.58)$$

After this standardization process, the final weight values are provided as 0.425, 0.334 and 0.241 for the total transport cost, total transit time and total CO₂ emission objectives, respectively. In summary, weighted additive model for intermodal freight transportation planning problem can be expressed by the following Eq. 5.59.

$$\left\{ \begin{array}{l} \text{Maximize } \sum_{k=1}^3 w_k \cdot \mu_k = w_1 \cdot \mu_{Cost} + w_2 \cdot \mu_{Transit-time} + w_3 \cdot \mu_{CO_2} \\ \mu_{Cost} \leq \frac{Z_1^U - Z_{Cost}}{Z_1^U - Z_1^*} \\ \mu_{Transit-time} \leq \frac{Z_2^U - Z_{Transit-time}}{Z_2^U - Z_2^*} \\ \mu_{CO_2} \leq \frac{Z_3^U - Z_{CO_2}}{Z_3^U - Z_3^*} \\ \sum_{k=1}^3 w_k = 1 \quad 0 \leq w_k \leq 1 \\ \text{Constraint set (4) - (43)} \\ 0 \leq \mu_{Cost}, \mu_{Transit-time}, \mu_{CO_2} \leq 1 \end{array} \right. \quad (5.59)$$

where w_k is the weighting parameter which represents the relative importance of fuzzy goals. After application of this approach to the proposed multi-objective load planning model, the following load plans given in Figure 5.20 can be provided for different transportation modes and outsourcing option. The computational results are gained for the present multi-objective multimodal load planning problem by applying different MOO approaches as presented in Table 5.10.

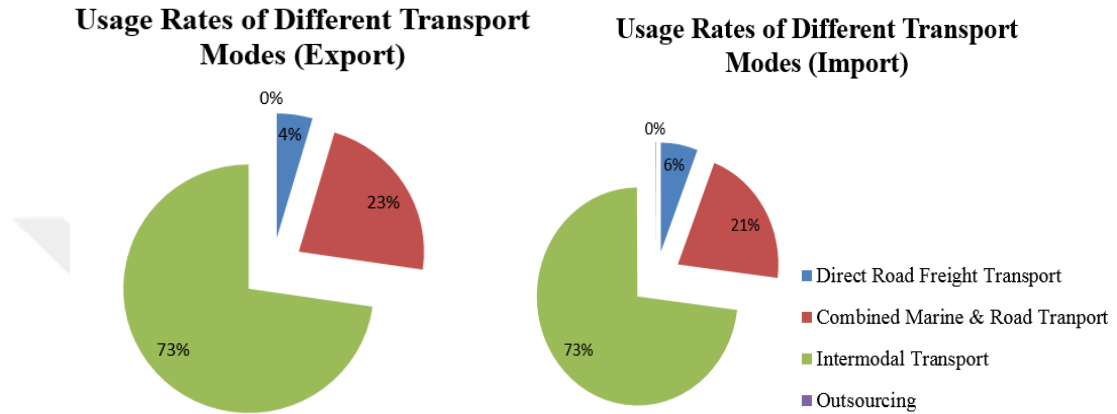


Figure 5.20 Usage rates of different transportation modes and outsourcing via weighted additive FGP approach

It is clear that the weighted additive FGP approach generates similar results with FGP-DIP approach in terms of cost and time objectives. Fortunately, superior environmental solutions can also be generated by using weighted additive FGP over the other FGP approaches.

Table 5.10 Fuzzy multi-objective optimization results via different MOO approaches

Objectives	FGP Approach with DIP	Weighted Additive FGP Approach	Compromise Programming Technique		
			($p = 1$)	($p = 2$)	($p = \infty$)
Total transport costs	154035453.9	154641905.4	153463526.9	153236616.8	153132940.9
Total transit times	8714199.96	8718974.96	8902431.08	8904681.96	8901790.58
Total CO ₂ emissions	104381954	102117156.2	101122368.78	101388463.1	101520707.6
Satisfaction degrees	0.83; 0.653; 0.506	0.782; 0.642; 0.778	N.A.	N.A.	N.A.
Model Class	MILP	MILP	MILP	MINLP	MILP
Total number of variables	35768	35768	35771	35765	35775
Total integer variables	35592	35592	35592	35592	35595
Total number of constraints	10771	10771	10765	10762	10772
Total non-zero elements	315822	315822	315822	315810	315841
Total number of iterations	1641506	56406	76618	1072699	124796
CPU time (sec.)	838.67	54.48	70.92	30885.16	104.42

5.4.2.4 Interactive Fuzzy Goal Programming Approach

The interactive fuzzy goal programming (IFGP) approach was first introduced by El-Wahed and Lee (2006) and applied to multi-objective transportation problems in order to determine the preferred compromise solution. In this approach, three most widely used methods namely interactive programming, goal programming and fuzzy programming were integrated in order to develop a more efficient approach which reflects the advantages of all these methods. In fact, this approach may improve the flexibility and robustness of the decision making process. From the perspective of a decision analyst, the most important advantage of this approach is controlling the search direction during the solution phase by updating both upper bounds and aspiration level of each goal for producing other efficient solutions (Selim & Ozkarahan, 2008). The solution obtained from the last iteration and accepted by decision analyst represents preferred compromise solution and perceived as a more realistic one (Subulan et al., 2015b). In contrast to the FGP-DIP approach which is discussed in Section 5.4.2.2 under group decision making environment, it is assumed that there is a single decision maker, i.e., board chairman of the logistics company, while applying interactive fuzzy goal programming process. After construction of the membership functions and determination of the aspiration levels, fuzzy MOO model can be transformed into the crisp equivalent single objective MILP model for the first iteration as formulated by Equation (5.57) where β is defined as an auxiliary variable.

$$\left\{ \begin{array}{l} \text{Maximize } \beta \\ Z_{Cost} + (Z_1^U - Z_1^*) \cdot \beta \leq Z_1^U \\ Z_{Transit-time} + (Z_2^U - Z_2^*) \cdot \beta \leq Z_2^U \\ Z_{CO2} + (Z_3^U - Z_3^*) \cdot \beta \leq Z_3^U \\ Z_{Cost} - Z_1^+ + Z_1^- = Z_1^U \\ Z_{Transit-time} - Z_2^+ + Z_2^- = Z_2^U \\ Z_{CO2} - Z_3^+ + Z_3^- = Z_3^U \\ \text{Constraint set (4) - (43)} \\ 0 \leq \beta \leq 1 \text{ and } Z_1^+, Z_1^-, Z_2^+, Z_2^-, Z_3^+, Z_3^- \geq 0 \end{array} \right. \quad (5.60)$$

The outline of the classical interactive fuzzy goal programming approach can be summarized as shown in the following Figure 5.21. It is assumed that the results of the first iteration whose membership functions are given in Figure 5.18 have not satisfied

board chairman of the logistics company yet. Therefore, former goals' bounds should be replaced by the newly obtained objective results from the first iteration. As a result, membership functions can be revised in the second iteration as shown in Figure 5.22.

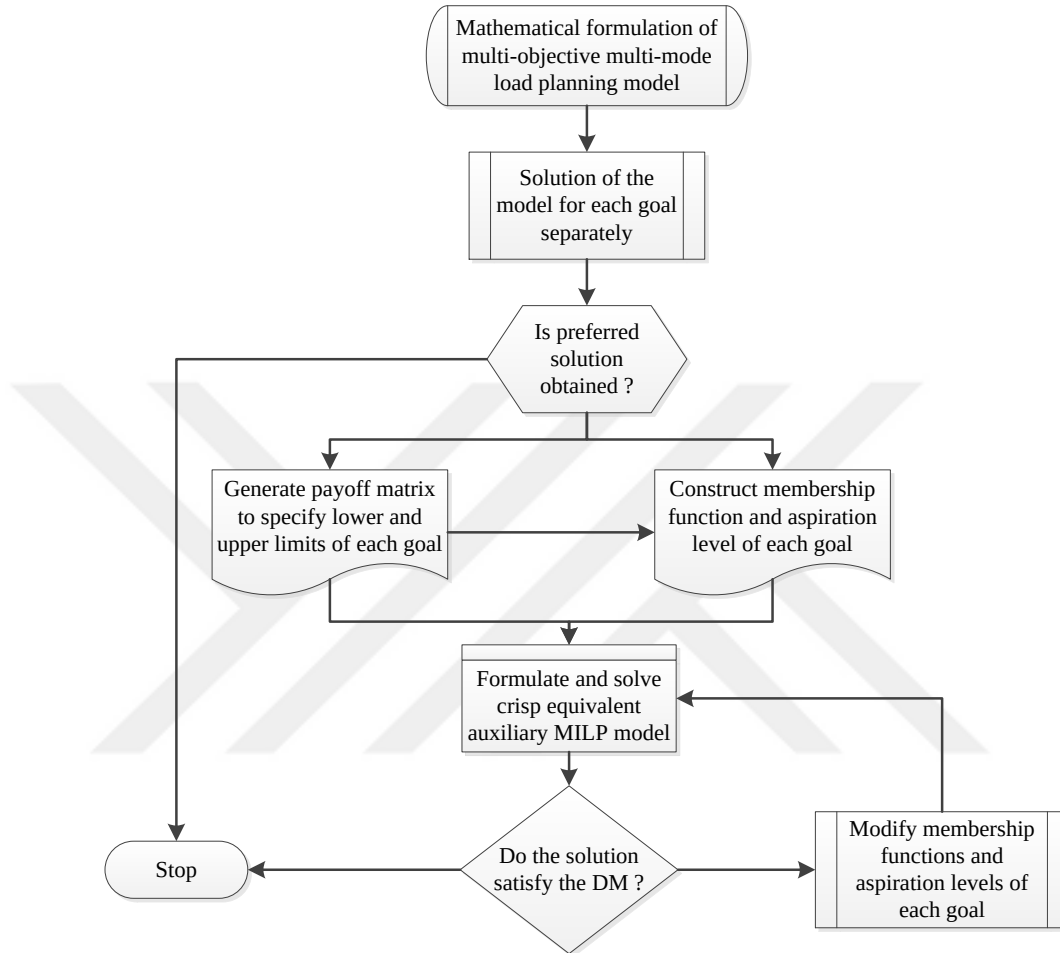


Figure 5.21 The application procedure of interactive fuzzy goal programming approach

In other words, membership functions are reconstructed in the second iteration. According to Figure 5.22, new aspiration levels of the objective functions are generated as 155486800.95, 8685542.15 and 102648540.6, respectively. Depending upon these bound revisions, the crisp equivalent auxiliary model given by Equation (5.57) is updated and resolved to produce the latter efficient solutions in the second iteration. Optimization results are provided by solving these auxiliary models iteratively as presented in Table 5.11. It is supposed that board chairman of the logistics company is satisfied at the end of the third iteration with the overall transport cost of €155479066.42 and accepts this solution as the preferred compromise solution. Thereby, the algorithmic procedure configured in Figure 5.21 is terminated.

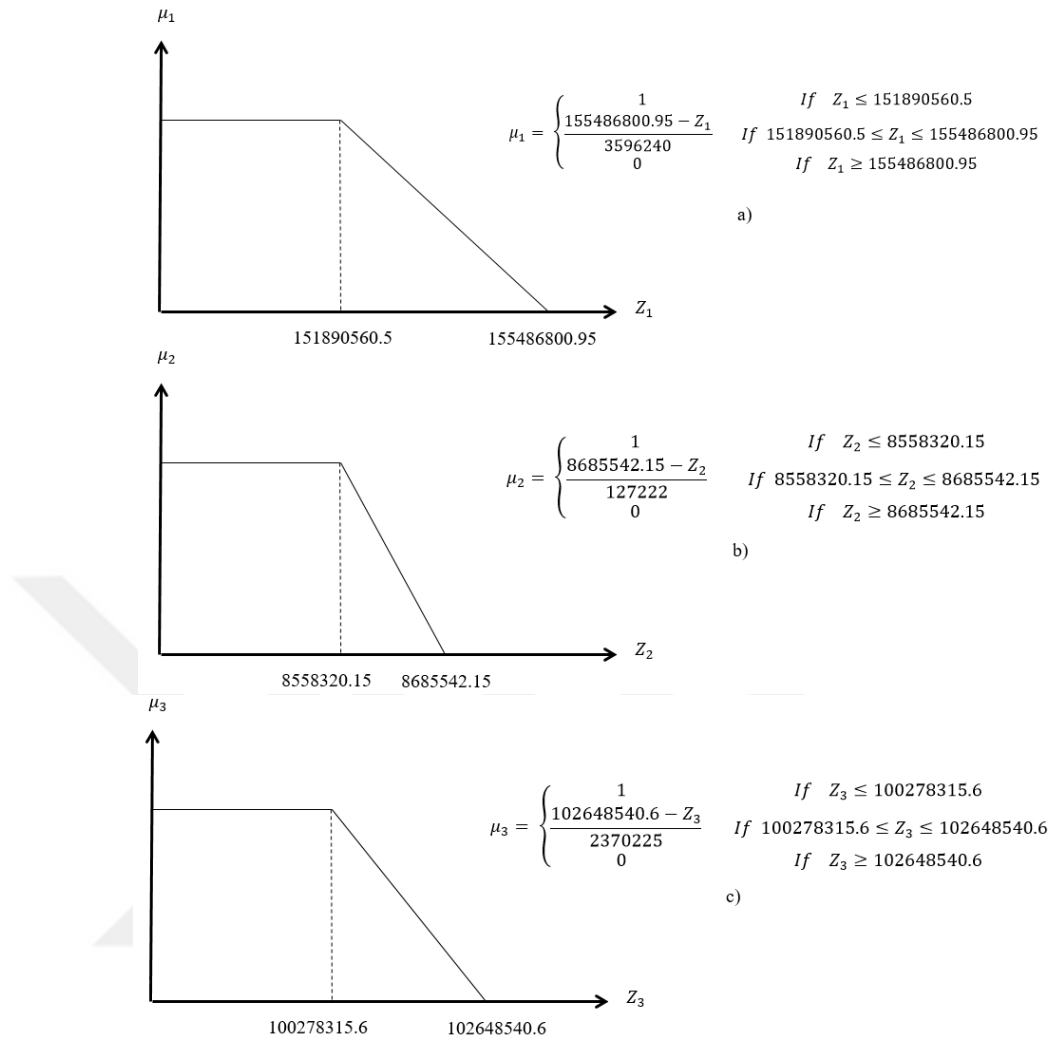


Figure 5.22 Membership functions in the second iteration: a) Total cost, b) Total transit time c) Total CO₂ emission

As shown by the Figures 5.20 and 5.23, similar load plans are derived from the weighted additive FGP and interactive FGP approaches. In detail, these approaches may provide nearby environmental impact values.

Table 5.11 Fuzzy optimization results by all iterations of interactive FGP approach

Iteration	Auxiliary variable β	Total Transport Cost	Total Transit Time	Total CO ₂ Emission	Solving time (Sec.)
1	0.7149	155486800.95	8685542.15	102648540.6	30.58
2	0.00172	155480611.85	8685450	102644128.21	104.33
3	0.000425	155479066.42	8685395.9	102642999.41	84.50
4		No feasible solution			

In addition, load plans with shorter transit times can be obtained by applying the interactive FGP approach. On the other hand, interactive FGP approach leads to more costly solution than all over the utilized MOO approaches.

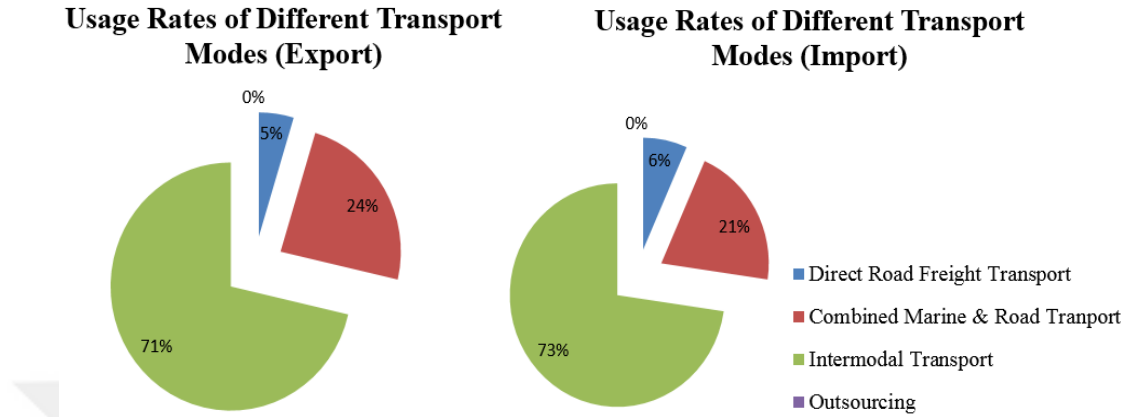


Figure 5.23 Usage rates of different transportation modes and outsourcing via interactive FGP approach (third iteration)

In addition to the usage rates of different transportation modes, variations of overall transport cost, transit time and CO₂ emission are also obtained from applying different MOO approaches as in Figures 5.24 – 5.26. When the computational results are evaluated, it is obvious that compromise programming approach with Chebyshev distance metric gives the best cost-oriented solution to the decision analyst under crisp environment. Again, CP approach with Pythagorean distance metric may also produce more environmentally conscious load plans.

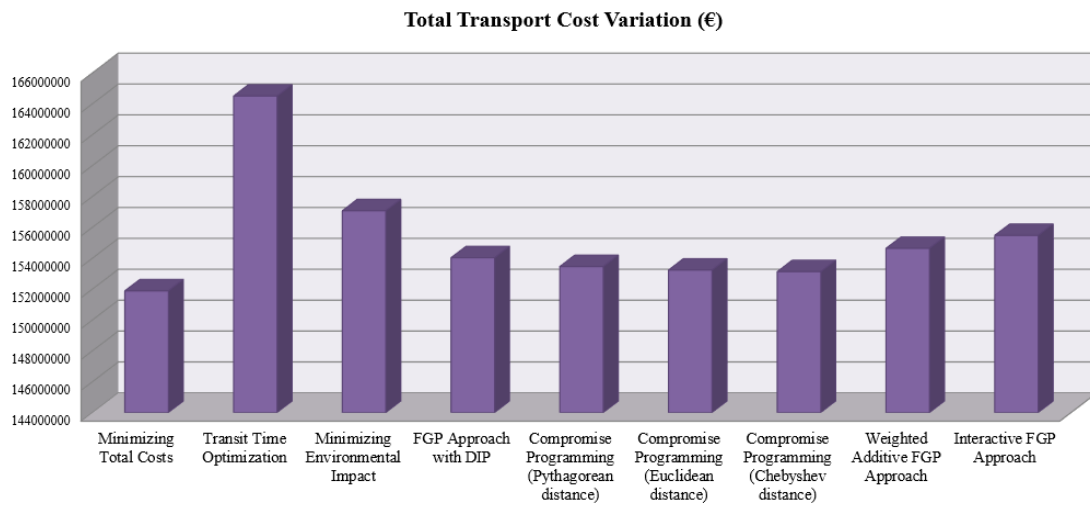


Figure 5.24 The total cost variation by single objective optimization and different MOO approaches

However, these approaches presented inferior results in terms of transit time objective when compared to goal programming based approaches under uncertain environments. Furthermore, it should be mentioned here that significant decrements in total transit time can be yielded via interactive FGP approach. On the other hand, this approach leads to more costly solutions over the other MOO approaches. The main components of the total transport cost, transit time and CO₂ emission objectives are shown by Figures 5.27 – 5.29 by applying different MOO approaches. Actually, Figure 5.27 displays that marine transport cost constitutes the large portion of total annual logistics costs. In addition, all MOO approaches gave similar marine transport cost values which are very close to the ideal solution of cost minimization.

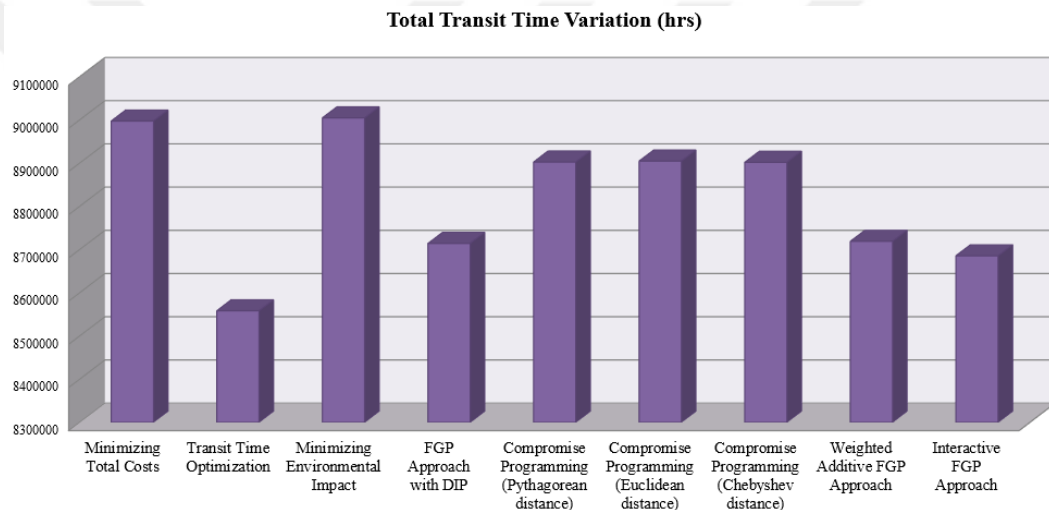


Figure 5.25 The total transit time variation by single objective optimization and different MOO approaches

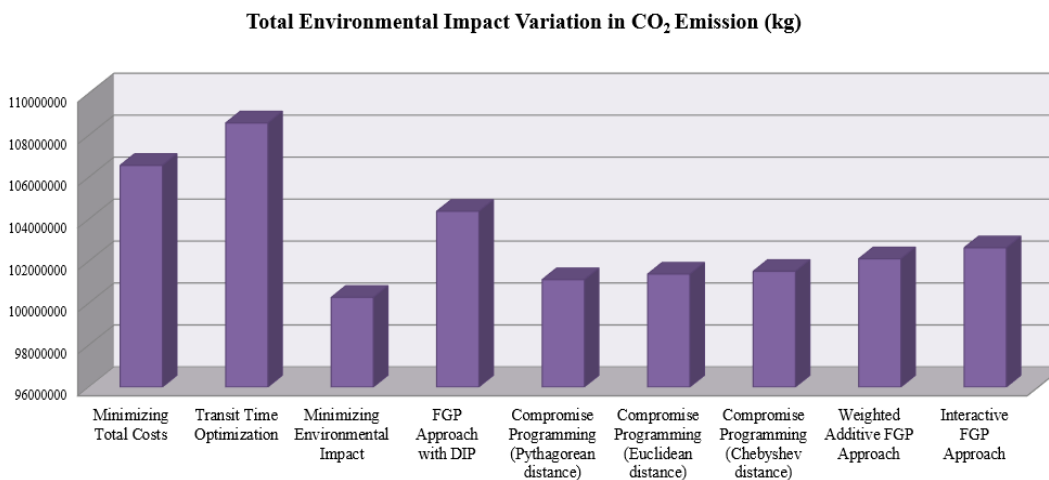


Figure 5.26 The total CO₂ emission variation by single objective optimization and different MOO approaches

It should also be noted here that application of MOO approaches provided almost zero outsourcing cost in opposition to the single cost objective optimization results. As it is clearly seen from Figure 5.28 that direct road freight transport provides the minimal transit times for freight transportation between Turkey and Europe as expected. Conversely, when the maritime and railway transport operations are involved, the total transit time will increase due to the increasing awaiting times at the terminals and long travel distances. Since the road freight transport is substantially utilized in outsourcing option, the regarding transit times have also short values. Briefly, intermodal and combined marine and road transports will cause longer transit times because of the slow average speed of electrical trains and long travel times of Ro-Ro vessels. In order to obtain shorter transit times in marine and railway transports, one can utilize FGP-DIP and weighted additive FGP approaches. When the environmental impact components are examined, it has demonstrated by Figure 5.29 that marine and road freight transports have significant effect on the environment since the large amount of CO₂ emitted. All of the used MOO approaches gave homologous emission values for maritime and railway transportation services. Fortunately, the minimal road freight environmental impact values can be obtained from CP approach by using Pythagorean distance metric while seeking a compromise solution among these conflicting objectives.

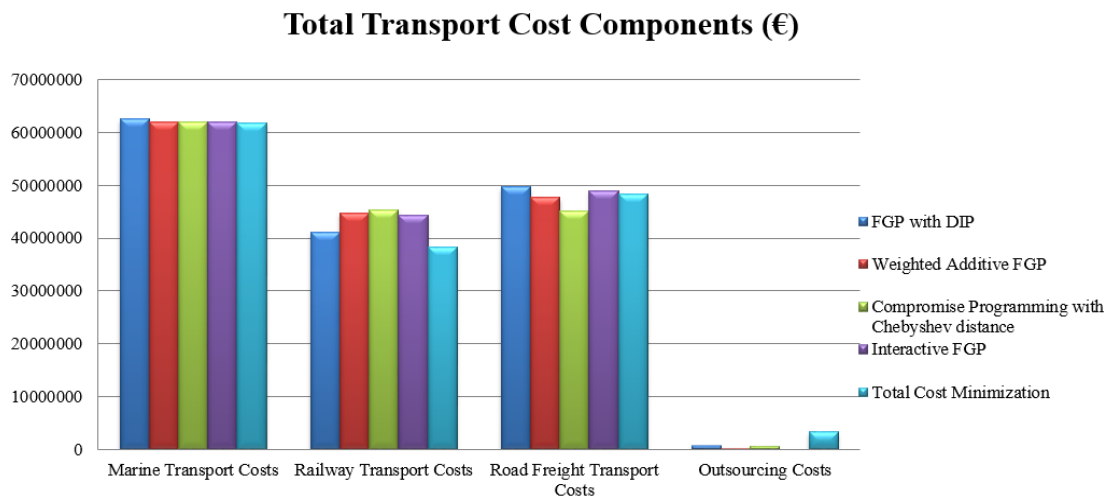


Figure 5.27 Components of total transport cost by cost optimization and different MOO approaches

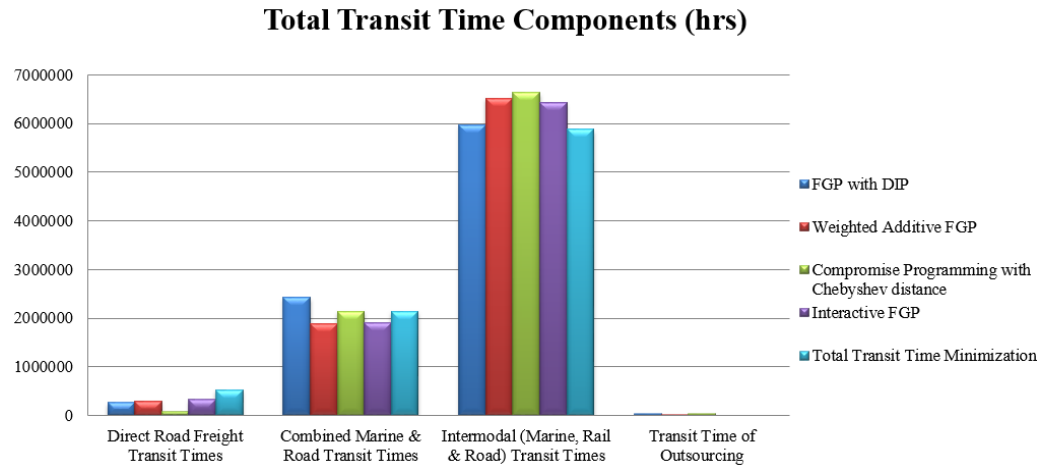


Figure 5.28 Components of total transit time by maximizing customer satisfaction and different MOO approaches

The import/export load quantities in marine transport by the company owned Ro-Ro vessels and the required number of block train services are presented in Tables 5.12 and 5.13. Actually, these are the load plans in marine and railway transportations and these results are provided by employing FGP-DIP approach due to the better reflection of the objective evaluations by multiple decision makers, i.e., intermodal operators of the logistics company, under uncertain environments. According to the computational experiments, most of the loads are transferred among the Istanbul and Trieste seaports in marine transportation by making use of the company-owned Ro-Ro vessels.

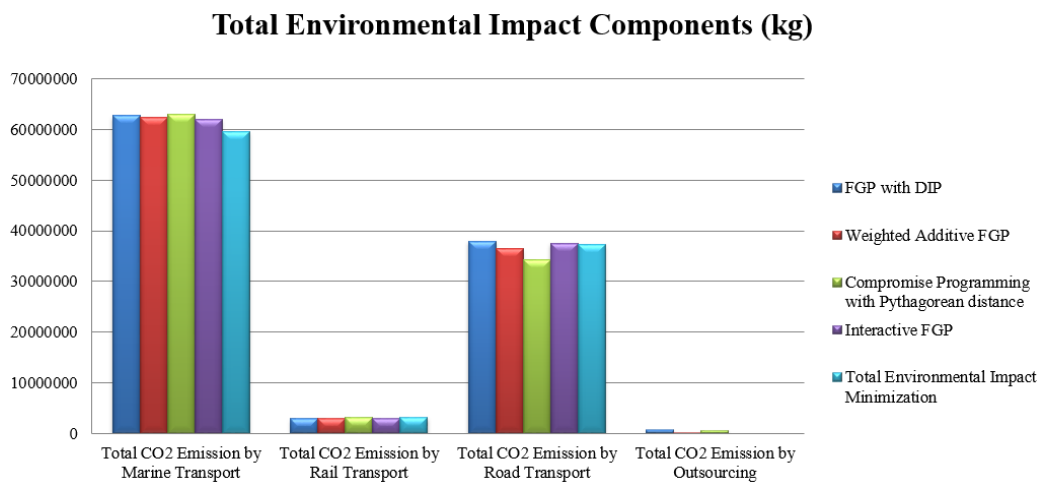


Figure 5.29 Components of total environmental impact by CO₂ emission optimization and different MOO approaches

For this reason, utilization rates of the regarding Ro-Ro vessels are comparatively high over the other marine links (see in Figure 5.30). It is also clearly seen from Table

5.13 that some of the transportation units are loaded or unloaded at the transshipment seaport, i.e., Lavrion, while realizing the maritime cruises among these seaports.

Table 5.12 Load planning in railway transportation

Months	Dec. 15	Jan. 16	Feb.	Mar.	Apr.	May	June	July	Augu.	Sep.	Oct.	Nov.
Number of trips for block train services												
Trieste/Ostrava	12	12	12	13	13	12	11	11	9	13	13	13
Trieste/Ludwig.	27	24	26	26	27	25	27	26	26	27	25	27
Trieste/Cologne	35	35	38	39	38	39	40	39	32	39	39	40
Ostrava/Trieste	13	12	12	13	13	13	12	12	8	13	12	12
Ludwig./Trieste	27	23	26	26	26	26	27	26	26	27	25	27
Cologne/Trieste	34	34	37	39	39	39	41	39	33	40	38	40
The import/export load quantities transferred by public trains												
Trieste/Munich	19	69	26	26	26	35	26	25	21	27	137	68
Cologne/Malmö	0	0	0	0	0	0	0	0	0	0	0	0
Cologne/Guthe.	147	142	164	166	158	156	147	150	135	168	152	156
Munich/Trieste	16	10	28	30	30	30	35	31	22	31	44	29
Malmö/Cologne	0	0	0	0	0	0	0	0	0	0	0	0
Guthe./Cologne	71	68	75	75	83	80	79	74	68	70	61	77

Table 5.13 Load planning in marine transportation

Months	Dec. 15	Jan. 16	Feb.	Mar.	Apr.	May	June	July	Augu.	Sep.	Oct.	Nov.
The import/export load quantities in marine transport by the company-owned Ro-Ro vessels												
İstanbul/Lavrion	35	37	36	40	38	40	38	39	17	40	38	39
İstanbul/Trieste	2514	2580	2578	2666	2635	2671	2633	2568	2256	2659	2832	2839
İzmir/Sete	177	275	213	234	225	291	233	197	160	234	300	297
Lavrion/İstanbul	16	20	18	17	17	15	17	16	14	13	18	17
Trieste/İstanbul	2466	2306	2525	2639	2633	2658	2722	2626	2269	2697	2540	2674
Sete/İzmir	187	188	199	207	203	206	201	186	170	187	200	204
The import/export load quantities in marine transport by the other logistics service providers' Ro-Ro vessels												
İstanbul/Trieste	0	0	0	0	0	0	0	0	0	0	0	0
İstanbul/Toulon	159	323	172	195	211	215	201	200	156	217	266	235
İzmir/Trieste	341	311	341	337	352	301	354	343	310	348	320	321
Mersin/Trieste	66	75	76	75	75	74	74	69	61	74	77	77
Trieste/İstanbul	0	0	0	0	0	0	0	0	0	0	0	0
Toulon/İstanbul	197	117	195	307	220	207	179	192	261	198	378	198
Trieste/İzmir	31	35	37	39	37	38	40	35	30	36	37	39
Trieste/Mersin	8	9	9	9	9	10	10	9	8	9	9	10

On the other hand, utilization rates of the company-owned Ro-Ro vessel which operates among Izmir - Sete seaports are slightly low because of the high transport costs of this speedy vessel. But, this Ro-Ro vessel has lower transit time and environmental impact since its high velocity and low load capacity. Apart from the company-owned Ro-Ro vessels, a bulk of loads is transferred by the other logistics providers' Ro-Ro vessels among the seaports of Toulon - Istanbul; Izmir - Trieste. Although, many export load transfers are available between Izmir - Trieste seaports, the amount of imported loads between these seaports is considerably low. When the number of required block train services is investigated, it is obvious that more block

trains should be chartered between Trieste - Cologne and Trieste - Ludwigshafen rail stations for both of the importation and exportation operations. Additionally, Table 5.12 shows that there is a balance between the import and export block train services at each month which fulfills the fixed scheduling limitations of block trains. In addition to the block train services which have full-than-train load characteristic, i.e., chartering the whole capacity of a block train, some of the loads should be shipped by public trains between Trieste - Munich rail stations. Actually, these trains have less-than-train load property and flexible time schedules. In other words, loads of the different logistics companies can be shipped simultaneously by this type of trains and do not require chartering the whole train capacity by the logistics company. Moreover, some of the loads arrived to Cologne transshipment rail station should be transferred by these public trains to Gothenburg station or vice versa.

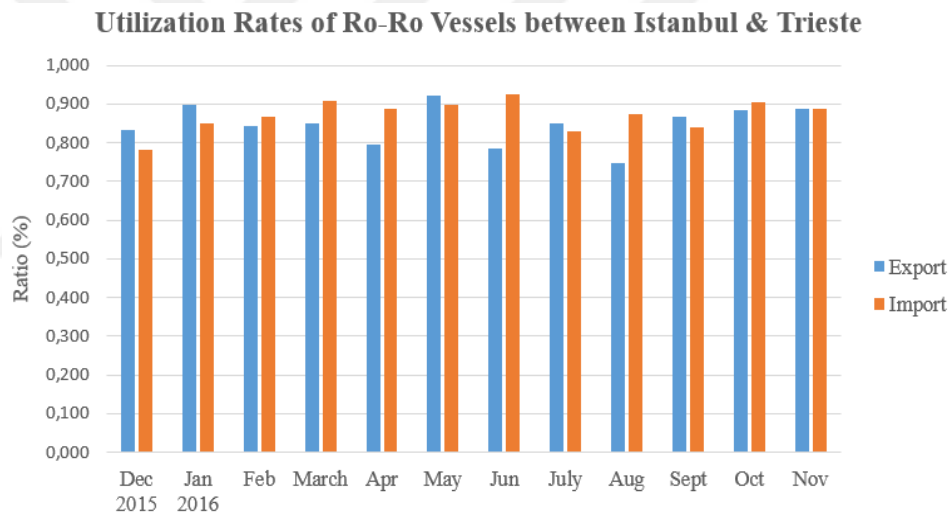


Figure 5.30 Utilization rates of company-owned Ro-Ro vessels operated between Trieste & Istanbul

It is obvious that all of the public train services are performed between Cologne - Gothenburg rail stations instead of using Malmö station. Finally, the monthly changes in total transit time and CO₂ emission goals are presented in Figure 5.31. The company experts evaluated the provided results and declared that effective and efficient load plans can be obtained by making use of the proposed multi-objective mathematical programming model. Therefore, the logistics company may provide sustainable competitive advantage by improving their load planning mechanisms which may contribute to the high level of customer satisfaction in addition to the possible cost and environmental damage reductions.

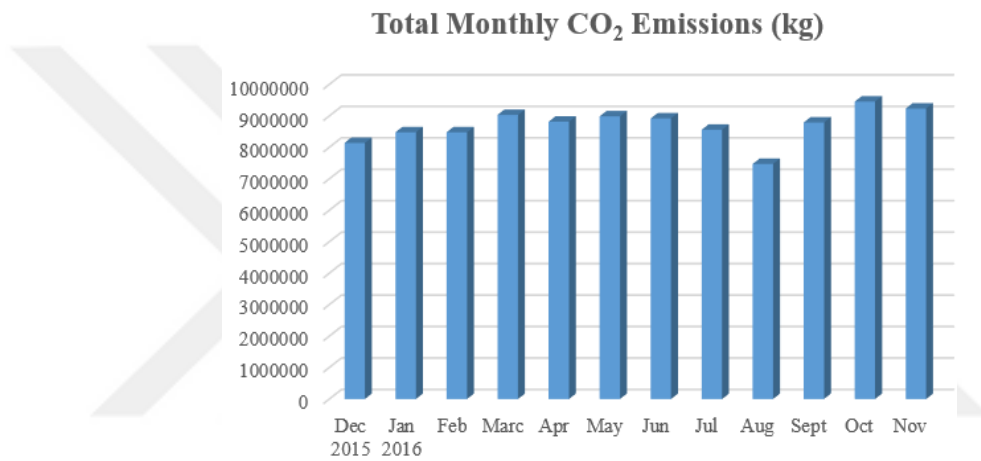
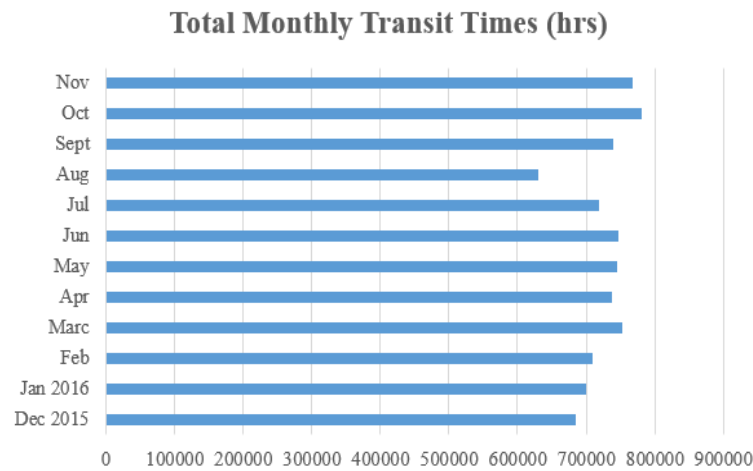


Figure 5.31 The variations of the monthly overall transit times and CO₂ emissions, respectively

5.4.3 Scenario Analysis for Managerial Insights

In order to investigate sensitivity of model parameters on the conflicting cost, time and environmental objectives and gain managerial insights related to the intermodal transportation system, the proposed load planning model is resolved with different values of marine transport cost between Izmir – Sete seaports, marine transport cost by the other logistics service providers, outsourcing cost per transportation unit, maximum number of marine cruises by the company-owned Ro-Ro vessels, upper bounds on the number of block train services, lower bounds on the utilization rates of the company-owned Ro-Ro vessels and specific portion of direct road freight transportation in outsourcing option, respectively. Scenario analysis is carried out in seven different scenarios using the application data as given by Table 5.14.

Table 5.14 Application data for scenario analysis

Scenario	Item	Run-1	Run-2
1	$Co_{ij}^{exp}, Co_{ji}^{imp}$	-50%	+50%
2	$Cp_{ij}^{exp}, Cp_{ji}^{imp}$	-10%	+10%
3	$SC_{ilt}^{exp}, SC_{lit}^{imp}$	-10%	+10%
4	$N_{ijt}^{exp}, N_{jit}^{imp}$	-25%	+25%
5	$UB_{jkt}^{exp}, UB_{kjt}^{imp}$	-30%	+30%
6	$LU_{ijt}^{exp}, LU_{jit}^{imp}$	>> 20%	>> 50%
7	φ^{out}	50% - 50%	25% - %75

According to the scenario analysis, decreases in marine transport cost between Izmir – Sete seaports and cost of the other logistics service providers' Ro-Ro vessels may provide possible reductions in terms of total transport costs (see in Figure 5.32). On the other hand, outsourcing costs have not considerable effect on the total cost of the intermodal transportation system. Although the marine transport cost between Izmir – Sete seaports is decreased down to the 50% percent of its current value, there will be only 1.8% improvement on the total transportation cost.

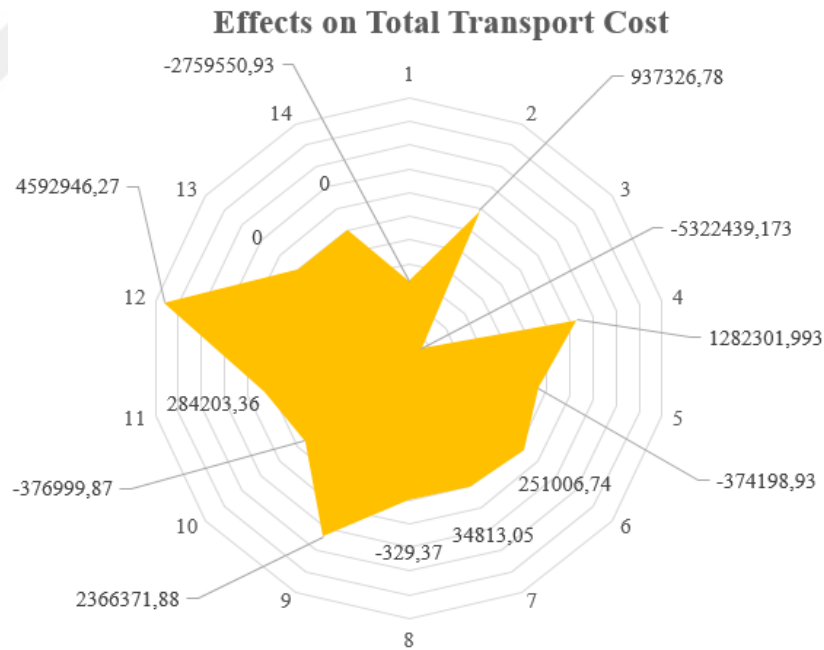


Figure 5.32 Increments and reductions in total transport cost as a result of all scenarios

In addition, cost of marine transport by the other logistics service providers is more influential on the overall transport cost than the cost of operating the company-owned Ro-Ro vessels. In detail, it is possible to provide approximately 3.5% cost reduction when the value of marine transport cost by the other logistics service providers is

decreased down to the 10% percent of its current value. For this reason, the logistics company should focus on the cost agreements and contracts with the other logistics providers rather than improving its own maritime operations. Moreover, all of these cost oriented scenarios have no impact on the total transit time and environmental objectives as clearly seen from Figures 5.33 and 5.34. Furthermore, as shown by Figure 5.32 that effects of the maximum number of available marine cruises and composition of the outsourcing option, i.e., direct road freight transport and/or combined marine and road transport, is virtually zero on the cost objective. When the upper bounds on block train services are decreased down to 30% percent of its present value, total transport cost value will increase up to €154256932.3. On the contrary, there is no significant impact of increments in the number of block train services on the overall cost of the system. The logistics company will be exposed to extra marine transport cost when an upper bound is set to the utilization rates of the company-owned Ro-Ro vessel operated between Izmir – Sete seaports. For instance, there will be 3% cost increment when the utilization rate of this Ro-Ro vessel is desired to have at least 70% level. From the perspectives of environmental and on time delivery objectives, there will be 1.7% and 4.3% increases in total transit time and CO₂ emission values when upper bounds on the number of block train services are decreased or these services will become more infrequent.

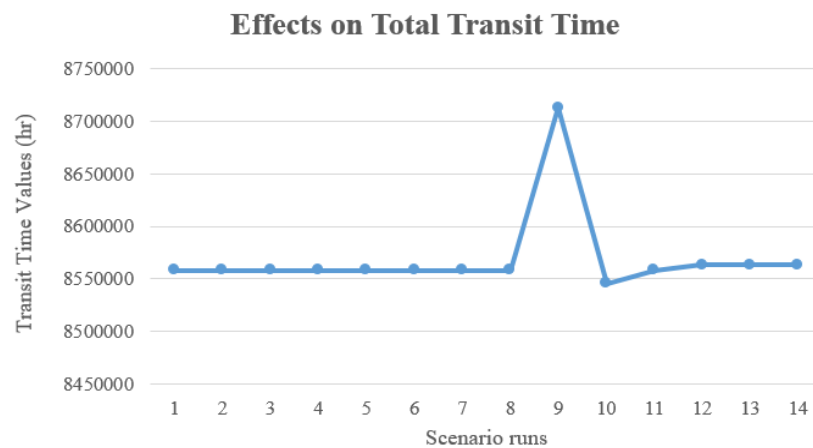


Figure 5.33 Variations of total transit time as a result of all scenarios

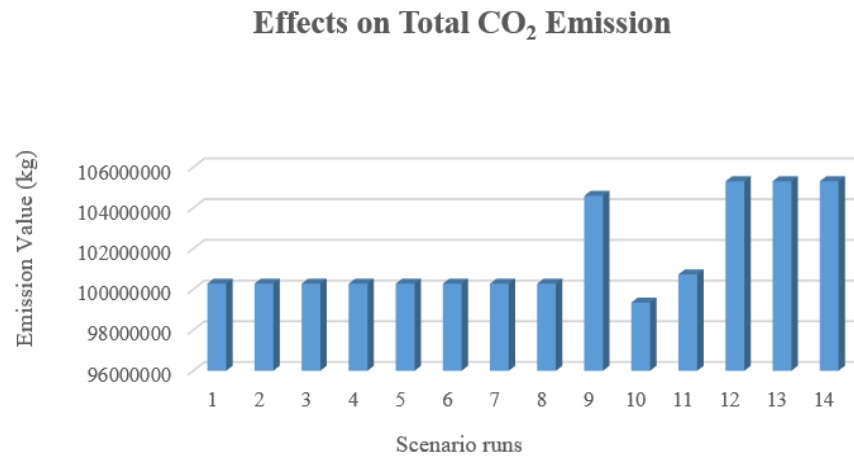


Figure 5.34 Variations of total environmental impact as a result of all scenarios

Fortunately, if the number of block train services is increased, both of the overall transit time and CO₂ emission objectives will reduce. It should also be mentioned here that there will be maximum 5.1% increases in CO₂ emission value when an upper bound is set to the utilization rates of the company-owned Ro-Ro vessel which operated between Izmir – Sete seaports. Furthermore, utilization rate of the Ro-Ro vessels do not have considerable effect on the transit time objective. In the original data, it is assumed that %75 percent of outsourcing operations are performed by direct road freight transport. When this ratio will increase up to %50 and 75% percent, there will be no impact on the transit time because of the limited quantity of load units transferred by outsourcing option when only the total transit time is optimized. However, when only the environmental objective is taken into account, total CO₂ emission will increase approximately 5% percent of its optimal value. Finally, the corresponding optimal logistics network configurations are presented in Figures 5.34 to 5.36 for direct road freight transport, outsourcing, combined marine and road transports and intermodal transportation, respectively. Actually, these logistics network configurations are just given for the total transport cost optimization because of its higher relative importance as aforementioned in Section 5.4.2.2. Actually, Figure 5.35 represents the import/export transport routes between Turkey and order countries via direct road freight transportation and outsourcing alternatives. Opposite to the load transfers by outsourcing, road freight transport operations are conducted between Turkey and its neighboring order countries because of proximity based cost objective.

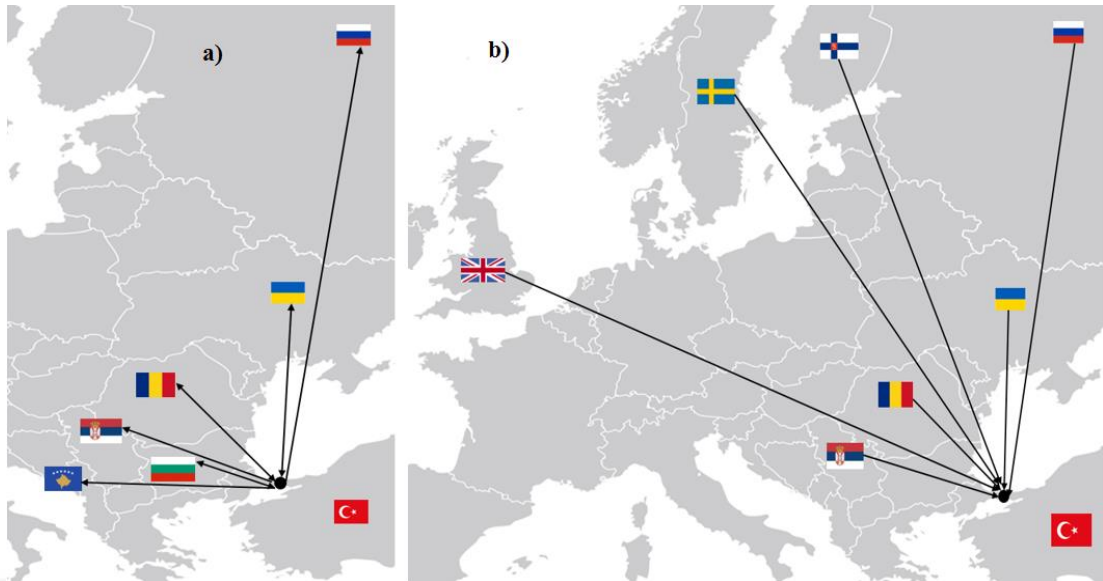


Figure 5.35 Logistics network configuration for a) direct road freight transport, b) outsourcing option

Also, when compared to loads of importation by direct road freight transport, the loads of exportation have larger quantities at each month. Due to this fact, there is no any load transfers by outsourcing option in the direction of exportation. In fact, only the importation operations are performed by the outsourcing option for the order countries which are far away from Turkey. Moreover, Figure 5.36 displays the routes of combined marine-road freight transport in which truckload shipping operations are made before/after the maritime logistics.

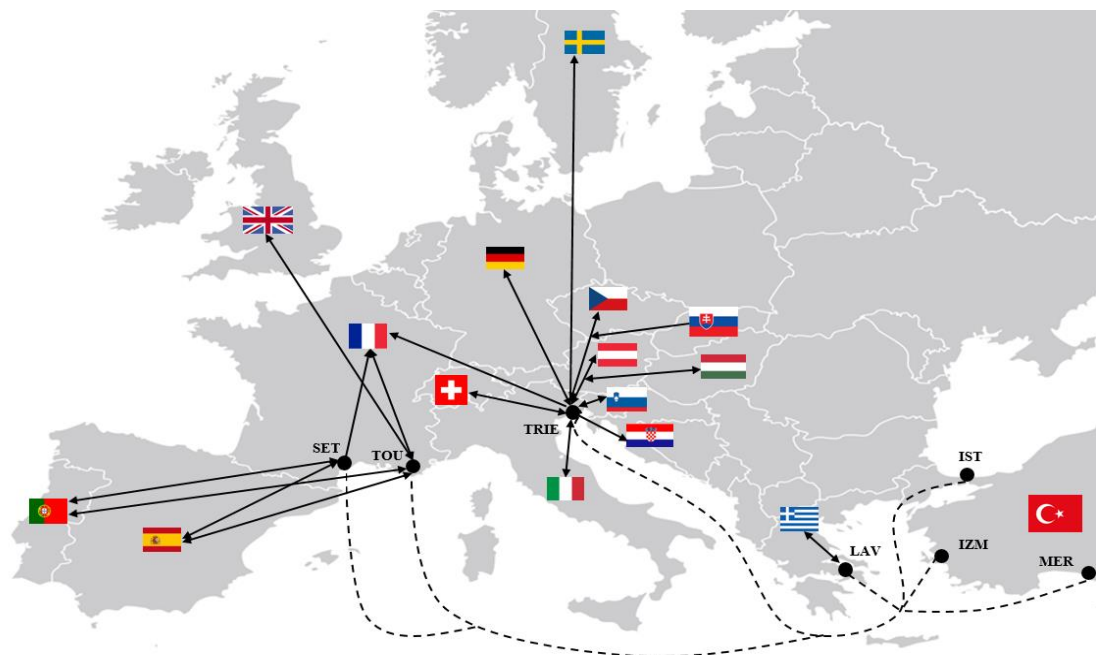


Figure 5.36 Import/export transport routes in combined marine and road freight transportation

It is obviously seen from Figure 5.35 that most of the maritime logistics operations are performed between Istanbul – Trieste seaports by the company-owned Ro-Ro vessels rather than Sete and Toulon seaports. However, there is also enormous number of load transfers between Izmir – Trieste and Istanbul – Toulon seaports by the other logistics providers' Ro-Ro vessels. The additional trailers or containers which are loaded or unloaded at the transshipment Lavrion seaport are also depicted in the same figure. These extra loads only fulfill the aggregated transport demand of Greece. It should be noted here that there is a balance among the importation and exportation load quantities in combined marine and road transport option. Lastly, intermodal logistics network of the company can be demonstrated by Figure 5.37.

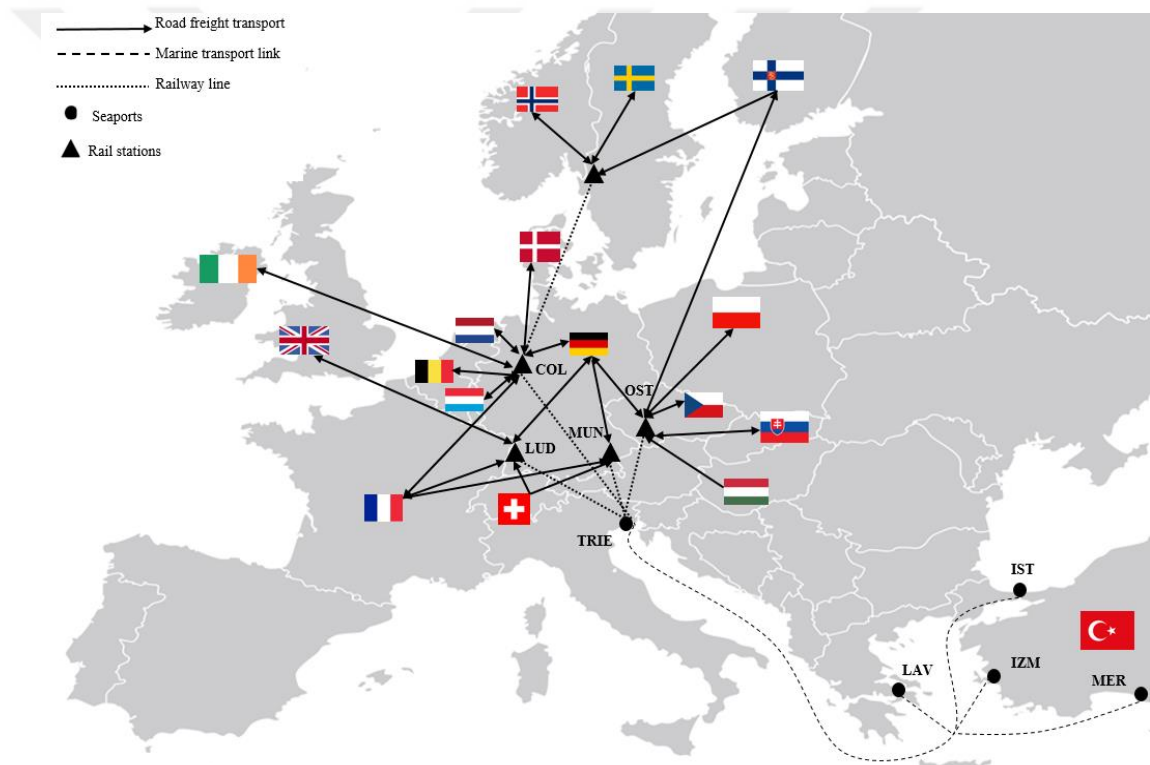


Figure 5.37 Intermodal logistics network configuration for the load planning problem in case of cost optimization

In this Figure 5.37, solely Trieste seaport is reflected on the logistics network as it is the unique seaport with several railway connections. Most of the loads are usually transferred by the block trains with fixed time schedules between Trieste – Cologne and Trieste – Ludwigshafen rail stations. In the direction of export, there is no any load transfer between Trieste – Munich rail stations. On the other hand, some loads are

transferred by using this public rail line for the imports into Turkey. In addition, it should be emphasized here that after the railway transshipment Cologne station, all of the loads associated with transport demands of some order countries such as Swedish and Norway will be shipped by the public trains via Gothenburg rail station. In other words, there is no need to utilize Malmö rail station for satisfying the transport demands of these order countries.

5.5 Chapter Summary

In this chapter, a novel mixed-integer mathematical programming model is developed to solve a multi-objective, multi-mode and multi-stage periodic load planning or intermodal freight transportation planning problem. Simultaneous flows of the import and export loads on the intermodal logistics network are also involved within the proposed model. Moreover, the proposed model also incorporates several important issues such as transportation mode and service selection, outsourcing, periodic load allocation, consolidation or exchange at the transshipment seaports/rail stations, usage of fixed scheduled block trains and public trains with flexible time schedules etc. In addition to minimize the overall transport costs throughout the intermodal logistics network consisting of outsourcing, marine, railway and road freight transportation costs, maximal customer service level satisfaction is also targeted by minimizing the total transit times. Furthermore, amount of total CO₂ emissions by the different modes of transport is also considered so as to provide environmental conscious load plans. In order to generate compromise solutions for these conflicting objectives, several multiple objective optimization approaches, i.e., compromise programming with different distance metrics, fuzzy goal programming with different importance and priorities, interactive fuzzy goal programming and weighted additive fuzzy goal programming, are employed under both crisp and fuzzy group decision making environments. A real-life application is presented in a large-sized international logistics company in Turkey so as to display validity and practicality of the proposed model. According to the computational experiments, intermodal transportation is the most appropriate way of freighting in terms of the economic, customer satisfaction and environmental objectives. Moreover, computational analysis of different multiple objective optimization approaches

suggested that compromise programming approaches with Chebyshev and Pythagorean distance metrics can present superior results in terms of the total transport cost and environmental impact goals. Additionally, load plans with shorter transit times can be obtained from interactive fuzzy goal programming approach under uncertainty of the aspiration levels of goals. The sensitivity of some model parameters, i.e., costs related to marine transport and outsourcing, number of block train services and bounds on the utilization rates of the company-owned Ro-Ro vessels etc. was also investigated by performing various scenarios. The scenario analysis have indicated that cost of marine transport by the other logistics service providers' Ro-Ro vessels is more influential on the overall transport costs than the cost of operating the company-owned Ro-Ro vessels. Moreover, availability of the monthly block train services has significant effect on both total transit time and CO₂ emission objectives. Finally, the company experts evaluated the generated results and enounced that effective and efficient load plans can be provided by making use of the proposed model. It is also revealed that the logistics company can obtain sustainable competitive advantage by improving their intermodal freight transportation planning mechanisms which may contribute to the high level of customer satisfaction in addition to the possible cost reductions. In the future, the proposed multi-mode load planning model can be extended to an intermodal fleet planning model by incorporating the fleet management issues including fleet size and composition, empty truck/trailer repositioning, fleet expansion/reduction and replacement decisions etc. Furthermore, development of a fuzzy-stochastic load planning model which is able to handle the uncertainty embedded into the transport demands, transit times, freight capacities and cost parameters may also be scheduled as a future work.

CHAPTER SIX
A MULTIPLE OBJECTIVE FUZZY & STOCHASTIC PROGRAMMING
MODEL FOR AN INTERMODAL HOLISTIC FLEET PLANNING
PROBLEM WITH A REAL LIFE APPLICATION

6.1 Chapter Introduction

Recently, modeling and solving fleet planning problems in intermodal transportation networks have received an increasing attention by both researchers and practitioners in the global logistics sector. However, most of the available studies in the literature were concentrated on single mode fleet management from the perspectives of logistics companies or production firms that generally utilize road freight transportation. In other words, there is a few papers on intermodal fleet sizing/composition problems when compared to the unimodal transportation systems. For the last two decades, because of increasing interests in intermodal transportation, the fleet planning problems need to be solved by handling various complex decisions simultaneously such as transportation mode selection, load allocation, outsourcing, sizing of maritime and railway cruises, empty vehicle repositioning, fleet allocation/reallocation, fleet expansion/reduction decisions etc. which make the problem much more complex. In fact, fleet size optimization have to be addressed in an integrated way with mode selection, load planning, vehicle allocation/reallocation, periodic truck/trailer inventories on the logistics network and empty vehicle repositioning problems. For this reason, fleet planning problems are much more complicated in intermodal transportation systems than unimodal road freight transport which considers only trucking part of the overall transportation system. On the other hand, intermodal fleet planning is composed of various complex issues at different decision levels. The decision hierarchy for intermodal fleet management is displayed by the following Figure 6.1. The details of the strategic, tactical and operational intermodal fleet management decisions can also be demonstrated by Figure 6.2. The fleet sizing/composition, terminal location, intermodal logistics network design, load planning, transportation mode selection, vehicle allocation/reallocation, outsourcing, empty vehicle repositioning, vehicle routing, Ro-Ro and train scheduling etc.

constitute the fundamental intermodal fleet planning problems. Actually, load planning or intermodal freight transportation planning is one of the most vital problem among them since influencing the other planning decisions directly. Because, outputs of the load planning problem are used as inputs by all of the other fleet planning issues. Unfortunately, existing studies in the current literature handled these problems in a separated way. Moreover, SteadieSeifi et al. (2014) emphasized that there are relatively few papers on operational planning problems than the strategic and tactical planning problems in intermodal transportation systems. Additionally, they also mentioned that there is no paper dealt with the dynamic positioning and repositioning problems of multiple assets or resources such as trucks, trailers, containers etc. The empty resource repositioning issues should also be covered by the fleet planning problems. Although the repositioning of these empty resources does not contribute to transportation profit directly, it is able to increase the customer service level by decreasing the awaiting time. Additionally, multi-objective intermodal fleet planning which considers the trade-offs among the cost, time and environmental aspects may find more research merit. They also reported that simultaneous planning of multiple resources, i.e., trucks, trailers, containers, drivers etc. and integration of backward flows (empty truck repositions) into the forward flows (loaded truck movements) will provide significant time saving and cost reduction. As it was also highlighted by Caris et al. (2008) that there are few researches in the literature which cover various time horizons and integrate the decisions of more than one decision maker. Based on these motivations, this chapter presents a holistic fleet planning model by incorporating the perspectives and objectives of several decision makers with different levels of decisions as it is obviously seen from Table 6.1.



Figure 6.1 Fleet management decision hierarchy in intermodal freight transportation

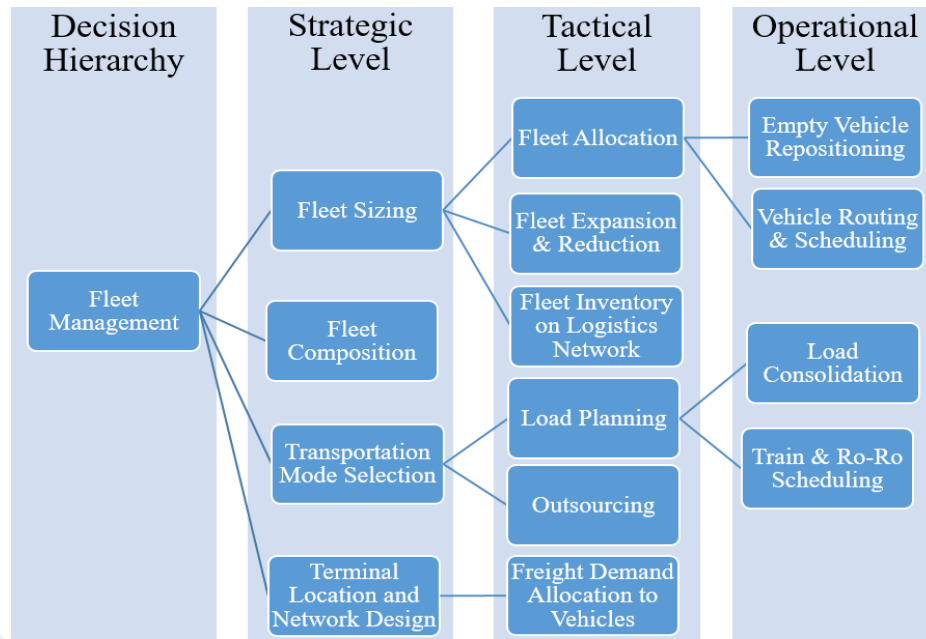


Figure 6.2 Strategic, tactical and operational level decisions on intermodal fleet management

The strategic level decisions of both drayage and terminal operators, tactical level decisions of both drayage and network operators and finally some operational planning decisions of all the decision makers are considered within the proposed holistic fleet planning model. For instance, determination of frequency of block train services and company-owned Ro-Ro vessels and allocation of resources, i.e., trucks, trailers, Ro-Ro vessels, block trains, to the service routes are the main tactical level decisions under the responsibility of network operator.

Table 6.1 Integration of multiple decision makers and levels into the proposed fleet planning model

Decision maker	Time horizon		
	Strategic	Tactical	Operational
Drayage operator	- Truck and trailer fleet size optimization considering the type of the truck plates (European or Turkish plates)	-Assignment of import and export load demands locations to terminals (seaports, railway stations)	-Internal repositioning for empty trucks and trailers which is resulted from the truck/trailer trip scheduling
Terminal operator	-Consolidation and exchange of load units at transshipment seaports and transshipment railway stations	N.A.	-Resource allocation (periodic truck and trailer assignments)
Network operator	N.A.	-Determine transport service types (direct road freight transport, combined marine and road freight transport and intermodal transport)	-Load order of block trains and company owned Ro-Ro vessels, -Assignment of trailers to European and Turkish plated trucks
Intermodal operator	N.A.	N.A.	-Transport service selection, -External truck/trailer reposition

For a better understanding, the proposed intermodal fleet planning model incorporates the following strategic, tactical and operational planning issues:

Strategic fleet planning decisions:

- Truck and trailer fleet size optimization,
- Truck fleet composition (type of truck plates - European and Turkish plates),
- Truck and trailer fleet expansion (purchasing new trucks/trailers) and reduction decisions (sales of second-hand trucks/trailers).

Tactical fleet planning decisions:

- Intermodal freight transportation planning (multi-mode load planning),
- Loaded truck movements, truck and trailer allocations to different road transport routes,
- Transportation mode and service type selection,
- Outsourcing,
- Periodic truck and trailer inventories on the intermodal logistics network.

Operational fleet planning decisions:

- Internal empty truck and trailers repositioning,
- External empty truck and trailer repositioning,
- Load consolidation at transshipment seaports and railway stations.

Coping with uncertainties such as stochasticity, dynamism and fuzziness related to the elements of an intermodal transportation system (stochastic transport demands, fuzzy transit times, mode capacities etc.) can be seen as the other major research challenges. Variability in transport demands, transit times and disruptions can be specified as the main sources of uncertainty in intermodal transportation. For this reason, it is supposed in this chapter that monthly import/export freight demands of the order countries are not exactly known and considered as stochastic parameters since they have randomness in nature. Moreover, since they may have epistemic uncertainty which is resulted from unavailability or incompleteness of the historical data, insufficient data etc., all of the cost parameters, transport capacities by marine and rail transports, transit times, number of working days at each month, truck and trailer availabilities, CO₂ emission values of different transport modes etc. are stated as fuzzy parameters and described by possibility distributions. In other words, these

parameters are taken as fuzzy data and represented by triangular fuzzy numbers in which pessimistic, most likely and optimistic values are determined by the company experts. In the light of this information, the proposed holistic fleet planning model is formulated as a fuzzy and stochastic mixed-integer program for the examined multi-objective, multi-mode, multi-stage, multi-resource, multi-period fleet planning problem with strategic, tactical and operational level decisions. Hence, different types of uncertainties, i.e., randomness and fuzziness, embedded into these aforementioned parameters can also be taken into account by the proposed model in an integrated manner. Because, real-life intermodal fleet planning problems may involve different types of uncertainties simultaneously. For this reason, the joint usage of stochastic programming and fuzzy mathematical programming techniques is required to solve this kind of problems. In this chapter, chance-constrained stochastic programming approach is employed in order to handle the uncertainty of transport demands. Furthermore, a popular fuzzy mathematical programming approach, i.e., resolution method of Jimenez et al. (2007), is selected from the literature so as to deal with the fuzzy model parameters. In detail, this resolution method is used to transform the proposed fuzzy fleet planning model into the crisp equivalent form.

Apart from the existing literature, both of the import/export transportation operations are considered in the load planning component of the proposed holistic model so as to satisfy the transport demands of the order countries consisting of aggregated customers. In addition to optimize the size of truck fleet with different plates, trailer fleet size is also determined by using transit times, period length or duration and truck/trailer availabilities. The repositioning decisions on both empty trucks and trailers are made by considering the periodic truck/trailer inventories on the intermodal logistics network. Besides, the proposed holistic fleet planning model incorporates the different service network design topologies simultaneously such as direct link, hub-and-spoke and connected hubs. In addition to minimize the overall transport costs, the proposed model also aims to minimize total transit time and environmental impact resulted from CO₂ emitted by different modes of transport. It is targeted to achieve maximal customer satisfaction or service level by minimizing the total transit times. Alternatively, the amount of total CO₂ emissions resulting from the usage of different transportation modes is also minimized to provide an environmental

conscious fleet plan. A weighted additive fuzzy goal programming approach is applied to handle these conflicting objectives simultaneously and obtain compromise solutions under different uncertainty levels. To the best of our knowledge, a similar fleet planning model which is studied through this chapter is not encountered in the current literature. The characteristics of the proposed holistic fleet planning model for intermodal transportation networks can be summarized as in Figure 6.3.

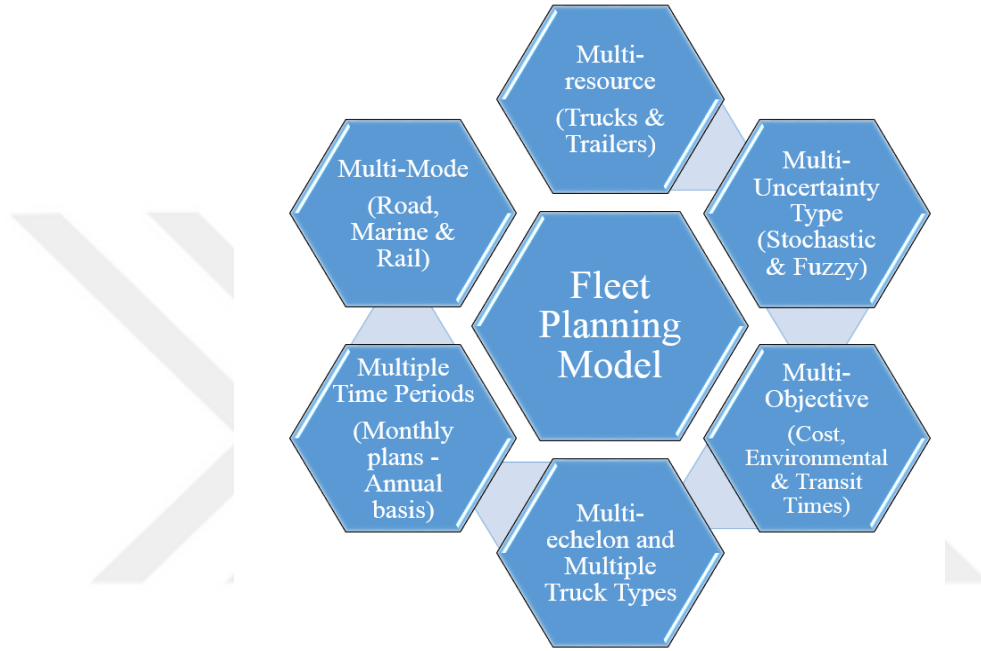


Figure 6.3 Characteristics of the proposed holistic fleet planning model in intermodal transportation

Finally, a real-life application is presented in large-sized international logistics company in Turkey for validity and practicality of the proposed model. The computational results show that the proposed model is able to provide meaningful contributions in generating effective and efficient fleet plans in intermodal transportation networks under fully uncertain environments. It is also revealed that logistics companies can provide sustainable competitive advantage by improving their fleet planning mechanisms that contribute to the high level of customer satisfaction and less environmental pollution in addition to the possible cost reductions.

The rest of this chapter is structured as follows. In Section 6.2, a comprehensive literature review on fleet sizing/composition in unimodal and multimodal transportation systems and overview of the articles which focused on empty vehicle repositioning problem are given. Section 6.3 presents the main components of the

proposed decision support system for the intermodal fleet planning problem with its model development phases for deterministic, fuzzy and stochastic cases. The details of the examined intermodal fleet planning problem with its mathematical model formulation are also expressed within this section. A hybrid chance-constrained stochastic programming and fuzzy mathematical programming based solution approach is described in Section 6.4. This section contains chance-constrained programming application with LINGO 15.0 optimization software and transformation process of fuzzy model into α -parametric crisp equivalent form. In Section 6.5, computational results of the deterministic, stochastic, fuzzy and fuzzy-stochastic fleet planning models are given for each objective function separately and compared to each other. Then, fuzzy multi-objective optimization results are provided for the fuzzy and stochastic case by applying a weighted additive fuzzy goal programming approach. Finally, concluding remarks and future works are presented in Section 6.6.

6.2 Related Literature

In this section, literature survey is divided into two main topics as fleet sizing/composition and empty vehicle repositioning problems in unimodal and multimodal transportation systems. The majority of the existing articles are reviewed and classified according to the problem/modelling characteristics, resource type, fleet structure, multi-objectivity, uncertainty issues and regarding solution methodology. Finally, deficiencies of the available studies and future prospects associated with intermodal fleet planning are discussed.

6.2.1 Literature Review on Fleet Sizing and Composition in Unimodal Transportation

The main principle of fleet size optimization problem is based on establishing a balance between the transport demand of the customers and service capacity of the logistics firm so as to determine the optimal number of vehicles. The fleet size optimization was mostly considered as a static, single-mode, single-period problem with homogeneous fleet by the early studies. After the increased interest in heterogeneous fleets, the problem structure was changed and become an integrated fleet sizing and composition problem. Fleet sizing and composition that are generally

emphasized on balancing the supply and demand are the most vital issues in strategic fleet management. Actually, effective and efficient fleet management may increase the economic efficiency of a logistic company and also affects the customer satisfaction. Fleet size optimization is not only associated with transport demand and service level but also it is highly connected with utilization of the vehicles. Actually, there is a significant interaction among the vehicle fleet size, fleet allocation and loaded/empty vehicle movements. The need for empty vehicle flows arises because of the unbalanced loaded truck movements on the logistics network. In other words, these empty flows are resulted from vehicle flow imbalances and cause additional repositioning costs. Therefore, empty vehicle inventories should be balanced throughout the entire transportation network. Because, there is a significant impact of an effective empty vehicle management on both operational and economic performance of the logistics companies. Empty vehicle flows should be reduced without decreasing the customer service level. Backhauling is one the most popular options for minimizing the empty vehicle travels (Dejax & Crainic, 1987).

The concept of fleet size optimization was first introduced by Kirby (1959). When the fleet size is too large, the utilization rates of wagons will be low. In the opposite case, the additional wagons required to be hired with extra costs in the case of too small fleet size. It was aimed to determine right the fleet sizes of owned and hired wagons which minimize total expected cost in a small railway system. According to his analytical expression and proof, if the cost of each owned wagon is 1 unit and hired wagons costing k units per day, then the current fleet size of owned wagons will be sufficient except for a proportion $1/k$ of all time periods. Wyatt (1961) extended the approach of Kirby (1959) by incorporating fixed (f) and variable costs (v) of per unit capacity for company-owned barges into the total transportation cost because of the barges have not generally a uniform size. Furthermore, the proposed expression was validated for periodic function of demand such as seasonal fluctuation for barge capacity required. According to his expression, the additional barges should require to be hired on f days in $k-v$ days. In other words, the proportion of the time in which additional hired barges are needed will be $f/k-v$ in the case of a seasonal demand. Moreover, it was also highlighted that possible cost reductions can be provided without shifting the fleet size by oversupplying along the low demand periods and utilizing the

company-owned barges and therefore avoiding the usage of hired barges with extra costs during the high demand periods. A linear programming model was proposed by Gould (1969) to determine optimal fleet size and composition of a large scaled industrial firm in order to satisfy the seasonal variations in customers' monthly demands. In their case study, there are two types of vehicles with six different sizes. In fact, the proposed model aims to determine how many vehicles company should have for each type and size. Piecewise linear approximations related to the hiring and variable costs were also included into the linear programming model by making use of separable programming. The fleet replacement, maintenance policy and timing of the vehicle purchasing was scheduled as a future work. A dynamic programming formulation was developed by Mole (1975) to improve the previous fleet sizing models by taking into account the time dependency of optimal fleet size. Through this dynamic programming model which was based on a regeneration process, the policy for timing of investments in new vehicles with respect to the seasonal demand fluctuations was also achieved. Indeed, optimal purchasing policy over the planning horizon was targeted while minimizing the piecewise linear convex costs. However, fleet size reduction or decreasing the number of vehicles from one period to another was not allowed by this dynamic program. Moreover, only one type of transport demand was considered by the dynamic program with a homogeneous fleet. A multi-period general linear model was developed by New (1975) for an aircraft fleet capacity planning problem which includes decisions on both fleet size and composition. The proposed model aimed to minimize the net present value of the total costs which can be calculated by summing of the flight operations costs, maintenance costs, depreciation expense minus sales of old aircrafts. Additionally, new aircraft purchasing, disposal of equipment, equipment replacement and allocation of the aircrafts to the appropriate routes were also taken into account by this model to meet all of the flight demands. The model was formulated by making use of various constraints such as demand satisfaction on each route, capacity limitations of owned aircrafts, aircraft inventory, budgetary and technological restrictions for new aircraft acquisition and finally restrictions on the sales of aircrafts.

A queuing-theory-based approximate method was developed by Parikh (1977) for solving a fleet sizing problem to allocate the available transport vehicle units to several

fleets for providing a uniform level of service by all of the fleets. Actually, the examined problem consists of two sub-problems namely fleet sizing problem and vehicle allocation problem. The fleet sizing problem was undertaken by a multi-server queuing system with Poisson arrivals and service rates. Service level was described as the time between placing of an order and its delivery time whose service time were represented by Erlangian distribution. The objective of the fleet sizing problem was to find the number of servers that the queuing system should have so as to delay probability does not get over a pre-specified threshold value β . A simulation model was constructed by Williams and Fowler (1980) for a minimum cost fleet sizing of a university motor pool where the distribution of vehicle demand, travel mileage and service time are not stationary. Then, a regression model was also presented to specify the appropriate fleet size among the various alternative fleet sizes. Computational experiments have showed that over 95% of all vehicle requests could be still satisfied even if the present fleet size was reduced by 30%. A mixed-integer linear programming model was developed by Etezadi and Beasley (1983) for a vehicle fleet composition problem. In detail, determination of optimal fleet composition for a central depot which serves several customers was intended in their study. In contrast to fleet sizing problems, not only the numbers of vehicle for each type but also the type of vehicles to operate are concerned by this fleet composition model. The proposed mathematical model also presented some long-term decisions to the decision maker such as the number of owned and hired vehicles for each type, the distance travelled by owned and hired vehicles in each time period and finally the expected distance travelled in each time period for both round trip and non-round trip cases. Gheysens et al. (1984) focused on a fleet size and mix vehicle routing problem and its existing solution methodologies. Firstly, this integrated problem aims at determining the proper fleet size and composition of a fleet with the vehicle routes while minimizing the sum of the fixed vehicle acquisition and routing costs. They formulated the problem as a mixed integer programming model. However, travel time restrictions and multiple routes for the vehicles were not taken into account by the proposed model. Finally, a novel two-stage heuristic approach which integrates a lower bound procedure and the generalized assignment heuristic of Fisher et al. (1986) was presented to obtain a proper solution. In detail, a lower bound which trade-offs the fixed cost against the

routing costs was calculated by solving a shortest path problem. In the first stage of the proposed heuristic approach, this lower bound approach results in the vehicle mix. Then, the assignment of the customer requests to different vehicles was obtained from the solution of a generalized assignment problem. Thereafter, a travelling salesman problem was solved to specify the delivery sequence of each vehicle. A decision support system based on a linear programming module was developed by Avramovich et al. (1982) for fleet management of a large sized truck transportation company in North America. In detail, planning and controlling of the company's tractor fleet were carried out to maximize the net contribution obtained from the sales of tractors with different model years, axle types to different customer types during a year. The financial impacts of the fleet management decisions and forecasted sales were also produced by the reporting module of the decision support system.

Turnquist and Jordan (1986) proposed a model for container fleet size optimization problem by considering deterministic production cycle and stochastic travel times. The containers were used to ship parts from a single manufacturing plant to a set of assembly plants. The production rate, usage rate and travel times, briefly production cycle can be seen as the key components of the proposed model while determining the container fleet size. The container shortage probability was also analyzed under different levels of travel time uncertainty. A comprehensive literature review on allocation/distribution of empty vehicles and fleet management models in freight transportation was presented by Dejax and Crainic (1987). The benefits of joint management of empty and loaded vehicle flows on the profit of logistics service providers were also discussed. They highlighted that one of the most important issues while modelling the fleet sizing and composition problems is the type of company. The company can be either a freight carrier or an industrial firm. Differences may appear in terms of objectives, problem characteristics, concepts etc. at both strategic and operational planning levels. Mathematical programming, stochastic optimization, queuing modelling, network algorithms (time-space networks), simulation modelling and metaheuristics are the most widely used solution methodologies for handling fleet planning problems. Finally, application of artificial intelligence techniques in fleet planning problems was given as future research opportunities.

A decision support system was developed by Couillard and Martel (1990) for planning the size and composition of a tractor fleet for a Canadian road carrier under seasonal stochastic demand. They presented a stochastic programming model which covers the plan for tractor purchase, replacement, sale and rental at a terminal. The proposed mathematical model also taken into account the type/age of tractors in the fleet and tax allowances related to the tractor ownership. They reduced the stochastic programming model to a two-stage separable program and solved by a grid refinement technique. A methodology was developed by Klineciewicz et al. (1990) for the strategic decisions in a material logistics system where the customers with daily random demands are served by a central warehouse. They aimed at determining the size of the private vehicle fleet, employing commercial outside carrier services or using the combination of them. In addition to determine the appropriate fleet size, the allocation of each sector in a geographical area to a private vehicle or to an outside carrier was performed by their methodology. They applied p -heuristic to specify appropriate number of vehicles than solved a single-source capacitated facility location model to discover which sectors should be served by a private vehicle or an outside carrier. A non-linear network optimization model was formulated by Beaujon and Turnquist (1991) for fleet sizing and vehicle allocation problem in a railroad transportation network. The objective of the model was to minimize expected costs resulting from the uncertainties in both demand and travel times. The interactions between fleet sizing and loaded/empty vehicle allocations were also involved within the proposed model.

An approximate solution methodology was proposed by Köchel (1997) for the integrated fleet sizing and redistribution problem by making use of the results obtained from a multi-location inventory model and Markovian decision theory. In detail, it was aimed at finding optimal allocation of the transportation capacities which composed of transport equipment, i.e., vehicles, containers etc. in a multi-location system while taking into account the redistribution of the free vehicles. The demand of each location was defined by a random variable which is assumed to be stationary and time-independent. The planning horizon was divided into several discrete time periods and expected discounted reward which is calculated by subtracting the penalty and transfer costs from the profit was tried to be maximized over the planning horizon. Du and Hall (1997) considered the fleet sizing and empty equipment redistribution problem with

stochastic freight demands in hub-and-spoke transportation systems. They formulated a theoretic model based on inventory and queuing theories with the aim of minimizing the fleet size to attain a desired long-run stock-out probability on vehicles. For deciding the stock-out probabilities as a function of the fleet size and also specify the control parameters, a decomposition approach was also developed.

A multiple objective non-linear integer programming model was formulated by Redmer et al. (2000) for fleet sizing problem in a road freight transportation company considering heterogeneous fleet. The proposed model depends upon queuing theory and aims to match between supply and demand as in the most of the fleet sizing models. The company-owned, external and commercial vehicles were serviced by the back-up facility of the transportation company. It was assumed that mean demand arrival rate and service rate have Poisson distribution. Maximization of the utilization index of both vehicles and back-up facilities and minimization of the amounts of subcontracted transportation orders were considered as the system goals. In the solution phase of the problem, a two-phase approach was applied. In the first phase, Pareto optimal solutions of the stated problem were derived. Then, in order to select the most satisfactory solution and evaluate these possible solution alternatives, different multi-criteria decision making approaches such as LBS, ELECTRE and UTA were utilized in the second phase.

A dynamic multi-period transportation model was developed by Zhao et al. (2001) for the vehicle composition problem including fixed routes and a single transshipment node. The transportation operations were performed by both company owned vehicles and hired vehicles since the uncertainty embedded into the freight demand. Inventory of the delivered products and travel times of the vehicles on each route were also involved within the proposed model. Since the NP-hard nature and complexity of the discussed problem, the problem was solved with a two-step approach. In the first step, a mixed-integer programming model was solved to obtain optimal transportation arrangements. Then, the problem was decomposed into sub-problems based on the multi-stage property of the problem and a dynamic programming model was developed as an exact solution algorithm. Analytical models were formulated by Imai and Rivera (2001) for strategic maritime refrigerated container fleet size planning

problem for both balanced and unbalanced trade cases. In addition to the loaded container flows in voyages between the ports, a flow of conservation of empty containers was also considered in a time-space network. They also developed a simulation model to designate the composition of refrigerated container fleet consisting of both own and leased under various different scenarios.

Köchel et al. (2003) developed a queueing network model for fleet sizing and empty vehicle reallocation problems. The mathematical formulation of the problem was also carried out by means of continuous-time stochastic models. They applied different reallocation policies to overcome the imbalance between the inflow of rented units and the demand. For the approximate solution of the problem, they presented a simulation optimization approach based on genetic algorithms. A two-stage stochastic programming model was developed by List et al. (2003) for fleet sizing problem of transportation services by incorporating the uncertainty related to the possible future demands and vehicle productivity. Purchasing of the new vehicles, retirement of the old vehicles, travel times and availability of fleet were taken into account while determining the optimal fleet size for different types of vehicles at each time period. In addition to owning and operating costs, service quality issue was also considered through the penalty costs for delaying and deferring shipments that are not satisfied within the allowable time window. In the stochastic optimization model, the fleet size variables were taken as first-stage decisions whereas fleet allocation decisions, i.e., vehicle flow variables, shipment delay and deferral were specified as the second-stage variables. Actually, problem was formulized by utilizing a robust optimization model which trade expected cost off against risk. In detail, downside risk measure which focuses on the scenarios whose total cost value is greater or equal to a threshold value was chosen as robustness criterion. Finally, stochastic decomposition approach was employed as a solution methodology.

A two-phase heuristic was developed by Koo et al. (2004) for fleet sizing and mix vehicle routing problem in a static container transportation environment where all of the transportation requirements are available to be picked up at the beginning of the planning period. In the first phase, a mathematical optimization model whose objective is to minimize the total empty vehicle time was utilized to obtain lower bound on fleet

size in the second phase. Actually, provided fleet size from the first phase was used as the initial solution in the second phase and improved by a Taboo search based algorithm for generating vehicle routes along with an optimal fleet size. The objective of that study was to minimize makespan for the vehicle routing plan with the usage of least number of vehicles. However, only one type of vehicle was considered. Computational experiments showed that Taboo search based approach outperforms than the other heuristics in terms of makespan and total vehicle travel time criteria.

Integer programming formulations and solution algorithms were presented by Avella et al. (2004) for path planning problem of fleet management and control systems. Actually, they desired to find the best path which satisfies the required conditions related to the physical, geometric, functional, urban and environmental characteristics of the road links in the transportation network. The problem was modelled by making use of the resource constrained shortest path problem for totalisable numerical road link characteristics such as length, travel time, fuel consumption etc. In fact, the proposed integer programming model corresponds to the shortest path problem with knapsack constraints. Branch-and-cut algorithm with a separation procedure was utilized to solve the problem without using sub-tour elimination constraints. The proposed models were tested on a real-life innovative fleet and Telematics system consists of low emission vehicles.

An integer linear programming model was proposed by Vis et al. (2005) to determine the minimum fleet size at a container terminal with lifting vehicles and capacitated buffer areas. They aimed at finding the optimal fleet size needed to transport all of the containers under time window constraints, i.e., release and due times. The allocation of the vehicles to the containers was also considered. Additionally, transportation of the several compatible containers by the same vehicle was taken into account. In order to decide the start time of the container transportation, the regarding time window was discretizing by generating a number of moments or possible start instants. Then, an acyclic and directed graph whose paths correspond to a sequence of containers that can be transported by the same vehicle was constructed. Based on this graph, an integer programming model was formulated so as to determine the minimum directed paths which also refer to the minimum number of containers.

Various simulation experiments were conducted to validate the results of the optimization model. According to the simulation experiments, nearby solutions can be obtained by the proposed optimization model for the number of vehicles needed to transport all the containers. A time-space network based linear programming model was developed by Wu et al. (2005) to determine the fleet size and composition in a truck-rental industry. In addition to the different truck capacities, ages and operating costs, operational (demand allocation, empty truck repositioning) and tactical decisions (capital decisions: truck procurement, replacement and sales) were also incorporated within the proposed model. On the contrary to deterministic demand, transportation times was stated as uncertain data and represented as stochastic parameters. A two-phase solution methodology was developed to solve large sized real-life cases where the problem is divided into smaller sub-problems by Benders decomposition in the first phase. In this phase, the customer demands were allocated to different assets by a demand-shifting algorithm. Then, the initial bounds and dual variables were utilized in the second phase to improve the solution quality by making use of Lagrangian relaxation method.

Papier and Thonemann (2008) proposed analytical models for fleet planning problem in a European cargo rail company. They modeled the rental process as a multi-server queuing loss system with a concave profit function. In their models, fleet size, fleet structure/composition and leasing strategy was considered under uncertainty of seasonal demand and rental time. In detail, a stationary queuing analysis was performed to provide structural results for fleet of owned and leased cars. A mixed integer programming model whose objective was to maximize the discounted value of the fleet cash flow throughout the planning horizon was developed by Qiuping et al. (2009) for a fleet planning problem. They also considered the multimode investment alternatives to fleet capacity expansion decisions. Their model not only took into account the building new ships, purchase or sales of second-hand ships, charter ships and scrapping old ships but also the ship deployment on each route and budget constraints for the investment strategies. In fact, their proposed model integrated fleet composition decisions with fleet scheduling problem under uncertain market environments. The restrictions on the operational time, investment capacity, ship selling or leasing quantities and ship age can be seen as the essential model constraints.

A multi-period mathematical programming model was developed by Moghaddam et al. (2009) for determining the fleet size, allocating the available rail-cars to several locations and redistribution of empty rail-cars. Because, there is a crucial interaction between the fleet sizing decisions and rail-car utilization decisions which are also affected by the rail-car redistribution strategy. The objective function of the proposed model was to maximize total profit which can be calculated by subtracting the total costs consisting of direct transportation cost, ownership cost, holding cost for idle rail-cars and penalty cost for unmet demand from the total revenue. It was also emphasized by the authors that optimal usage of empty rail-cars provides decrease in rail-car purchasing costs and increase in the rail-car utilization. Furthermore, in order to solve the large-scaled problem instances in a reasonable computation time, a meta-heuristic solution approach based on Simulated Annealing was proposed. Development of a multi-objective optimization models which are also able to handle stochastic nature of rail-car demands and travel times were given as future research directions. A simulated annealing approach was developed by Sayarshad and Ghoseiri (2009) to solve multi-period rail-car fleet sizing and freight car allocation problem where the unmet demand of the customers can be backordered. Firstly, they proposed a deterministic mathematical programming model which is able to provide some information about yard capacity, unmet demands, fleet size of rail cars, allocation of the freight cars, amounts of loaded and empty rail cars at any given time and location. Then, a simulated annealing algorithm is proposed to solve medium and large sized problem instances due to the computational complexity of the proposed model.

A simulation optimization procedure based on genetic algorithms was proposed by Dong and Song (2009) for integrated container fleet size optimization and empty container repositioning problem in a stochastic dynamic liner shipping system composed of multi-vessels, multi-ports and multi-voyages. The main goal of that study was to minimize the expected total cost which involves various cost items such as inventory-holding, lifting-on/lifting-off, transportation, repositioning and lost-sale penalty costs. The computational results have demonstrated that more reliable customer demand can lead to reduction in fleet size and inventory levels at the seaports. A two-stage stochastic programming model was proposed by Sayarshad and Moghaddam (2010) for optimizing the rail-car fleet sizing and freight car allocation

problems under demand uncertainty. The simultaneous flows of loaded and empty rail-cars throughout the logistics network was also considered. In that study, they emphasized on the interaction between the strategic fleet planning and tactical rail-car repositioning issues. In addition to unmet demands, loaded and empty rail cars, rail-car inventories at the end of each planning period can also be determined. The objective function was to maximize total profit which is calculated by subtracting the summation of operating, ownership, holding and penalty costs from the total revenue obtained from the transportation services with loaded cars. In order to handle uncertainty related to the transportation demand, five different scenarios with equal occurrence probability were generated. The initial good solutions which represent the loaded rail-cars quantities were obtained from the first-stage mathematical formulation. Then, these solutions were improved and values of second-stage decision variables were yielded by utilizing simulated annealing algorithm. Finally, stochastic model results were compared to the deterministic model solutions and sensitivity analysis were performed on the number of time periods and network locations.

Redmer et al. (2012) formulated two distinct mathematical models for the fleet composition problem of a medium-size fuel distribution network. In fact, the proper number and types of road tankers was aimed to determine in order to transfer fuels from the central depot to the several gas stations. Maximum working time of the drivers, restriction on the capacity for chambers of the vehicles, fuel demand satisfaction and not mixing the different types of fuel in the same chamber were highlighted as the main constraints of the developed models. Minimization of the total daily distribution cost and maximization of the average fleet capacity utilization were taken as the objective functions. The assignment of different types of tankers to the gas stations and allocation of the specific types of fuel to the tankers and their chambers were defined as the decision variables. In the first mathematical formulation of the problem, the assignment decisions were made by considering the list of the all vehicles. Thus, the demand of any gas station was assigned to a specific tanker. In contrast, the demand of each gas station was assigned to the particular type of tanker in the second mathematical formulation. A hybrid local search and Genetic algorithm based meta-heuristic approach was applied for solution of the problem because of the high computational effort needed for the real-world problem instances.

A mixed-integer programming model was developed by Cheon et al. (2012) for a railcar fleet sizing optimization problem in chemical industry. They desired to find the optimal fleet procurement plan which determines among buying or leasing options. In contrast to the traditional fleet sizing approaches, proposed model considered the usage of railcars for not only transportation operations but also for the inventory storage space of the production site while establishing the optimal fleet size. In other words, in addition to the demand forecasts, production schedule and inventory policy were also taken into account while computing the best fleet size. For that reason, there is need to define statuses of the railcars which were categorized as empty, inventory or in transit. In addition, car modification which allows transformation one car type to another type was also included within the proposed model. The railcars that belong to different status such as existing cars, new acquisition cars, retired cars and qualified cars were allocated to the various tasks in different business groups. Computational results displayed that superior results can be provided by their optimization model when compared with the rule-based simulation approach. Developing new stochastic programming models which have ability to handle uncertainty in demand rate, transit times etc. was suggested by the authors for future researches.

Most of the transportation companies attempt to improve customer service level by minimizing the probability of truck unavailability or lowering the customer waiting times. Additionally, they often require to determine the optimal fleet size since the customer demand is seasonal and the trip times are also uncertain. For this reason, Roy et al. (2013) modelled the fleet sizing problem via multi-server queuing system with the aim of determining optimal number of trucks to achieve the desired service level. To do this, order arrival process (nonstationary customer demand) was modelled by utilizing a Markov-modulated Poisson process. Additionally, the service time which includes vehicle unavailable time or waiting time and trip time was represented by an exponential random variable. A continuous time Markov chain was used to estimate the average customer waiting time probabilities. In detail, a state-transition-rate diagram was drawn to represent the states in the Markov chain. Then, a generator matrix was constructed to represent the steady state relations. Finally, steady state probabilities which are used to estimate customer waiting time probabilities were obtained by solving the generator matrix via Gaussian elimination technique.

Deterministic linear and non-linear network flow models were developed by Carbajal et al. (2013) in order to specify the proper fleet size and investigate the effects of additional tractor repositioning on the fleet size in a less-than-truckload company. In contrast to the existing researches in the literature, they did not emphasize on the operational repositioning/redistribution of empty vehicles with the purpose of balancing resources throughout the network. Actually, it was considered that extra repositioning moves may be beneficial in terms of decrease in fleet size. For modelling framework, they utilized event-based and time-expanded networks under different repositioning strategies which are either flexible or structured ones with repeatability requirements. In fact, these strategies may result in different fleet size reductions. Moreover, linear and non-linear cost structures were used to assess the conflicts between fleet size costs and empty tractor repositioning costs. According to the computational results in a real-life national carrier, cost savings up to 5% can be provided by performing additional flexible repositioning strategies.

A decision support system depending upon a micro-simulation model was developed by Caggiani and Ottomanelli (2013) for dynamic bike relocation process in a bike sharing system consisting of fleet of bikes, bike stations and users. Since the unbalanced distribution of the bikes over the time and space, appropriate redistribution process is required so as to balance the demand and supply, increase system capacity and users' satisfaction. In addition to determine the optimal repositioning flows, time intervals between the redistribution operations, alternative route choices for redistribution trucks and demand variability were also taken into account within the proposed model. The decision variables were defined as the number of stations and their locations, size and capacity related to the redistribution trucks at each station, number of docking slots and total number of bikes etc. Each operating day was divided into several time intervals. In order to forecast the demand of bike requests, feed-forward back-propagation neural networks was utilized in the proposed decision support system. Moreover, a fixed point non-linear integer programming model was developed to obtain the optimal relocation matrix and relocation path of the redistribution trucks. According to the computational results, the proposed decision support system which considers the relocation issues provided may decrease the number of lost users and increase the user satisfaction.

Since the customer transportation requirements are generally satisfied by heterogeneous vehicle fleets in most of the real-life distribution networks, Koç et al. (2014) developed an integer linear programming model and a novel hybrid evolutionary meta-heuristic algorithm for fleet size and mix pollution routing problem (PRP) with time windows. The objective function of the proposed model was to minimize the sum of vehicle fixed costs, fuel consumption costs, CO₂ emissions costs, and driver costs. The only constraint of the model related to the fleet size was the limitations on maximum number of vehicles for each type. The other constraints were similar as in the classical vehicle routing and pollution routing models. Actually, the proposed hybrid evolutionary algorithm incorporates a heterogeneous adaptive large neighborhood search strategy as a main education component and it was combined with a speed optimization algorithm to optimize the speed of each vehicle on each segment of a given route. Computational results have displayed that optimizing the size and vehicle speed in a heterogeneous fleet is more meaningful and useful than homogeneous one.

A new solution method was proposed by Louwerse et al. (2014) for movement scheduling problem in a multi-hub express network of a service provider. The movement scheduling problem involves two distinct parts namely scheduling movements between depots-hubs and scheduling movements between hubs. These sub-problems were formulated separately by using integer programming. The proposed models considered heterogeneous vehicle fleet, different service types, timing of movements, empty vehicle repositioning, allocation of the capacity to the arcs and routing of the flows. In order to formulate the scheduling movement problem between depots and hubs as set partitioning problem and reduce the problem size, composite variable approach was used. The quadratic constraints into the integer programming formulation were linearized with additional binary variables. Then, column generation algorithm was used to solve this first scheduling problem. The other movement scheduling problem between hubs was formulated as a network loading problem and solved with a local search algorithm. The timing of movements was handled by using time-expanded directed graph where the nodes represent the hubs in the given time period. In the overall solution method, these scheduling problems were solved sequentially and then repositioning cost was determined by using their results.

A novel modular heuristic algorithm which depends on the sequential paradigm was presented by Vahed et al. (2015) to solve fleet sizing problems for multi-depot and periodic vehicle routing problems. The three fundamental constraints namely vehicle capacity constraint, route duration constraint and budget constraint were considered while minimizing the total number of vehicles needed at each depot. Their proposed iterative modular heuristic algorithm includes three phases which correspond to the allocation of the customers to the visit patterns, depot assignment to the customers and design of routes for each period and depot, respectively. The path representation was utilized for solution encoding and elitism strategy was also used to keep both high-quality and high-diverse solutions in the reference sets. In the visit pattern assignment procedure, an integer programming model was formulated to minimize the total squared Euclidean distance among the customers' locations and reference point location which was pre-determined by using a memory-based algorithm. Apart from the existing literature, the parameters of this integer programming model were adjusted dynamically according to the search process. The decisions on depot assignment were made by solving a clustering problem for each time period. In the last decision, the route design was obtained by a heuristic including three different steps namely construction, splitting and finally improving steps. According to the computational experiments on different problem instances, proposed modular heuristic algorithm generates superior results in a reasonable time when compared with the Generalized Unified Taboo Search algorithm.

Most of the previous studies mentioned in this literature survey can be summarized as given in the following Table 6.2. In fact, the existing articles in the literature are categorized with respect to the resource type (truck, trailer/container, wagon, tanker, aircraft, rail-car, ship etc.); fleet structure (homogeneous or heterogeneous); type of the fleet planning problem (fleet sizing, fleet composition or both); modelling characteristics (multi-objectivity, multiple periods); problem characteristics (static or dynamic); inclusion of load and fleet allocation, empty vehicle repositioning issues, fleet expansion/reduction, outsourcing and vehicle routing problems; uncertainty issues (deterministic, stochasticity or fuzziness) and relevant solution methodology.

Table 6.2 Problem and modelling characteristics of fleet sizing and composition problems in unimodal transportation systems

Article	Resource Type	Fleet Structure	Fleet Problem	Load Allocation	Fleet Allocation	Empty Repositioning	Vehicle Routing	Outsourcing	Fleet Expansion/Reduction	Multi Objective	Multi Period	Problem Characteristics	Solution Methodology
Kirby (1959)	Wagon	Homogeneous	FSP	-	-	-	-	-	-	-	-	Continuous Deterministic	Analytical Modeling
Wyatt (1961)	Wagon	Homogeneous	FSP	-	-	-	-	-	-	-	-	Continuous Deterministic	Analytical Modeling
Golud (1969)	Tanker	Heterogeneous	FCP	✓	-	-	-	✓	-	-	✓	Dynamic Deterministic	Linear Programming
Mole (1975)	Vehicle	Homogeneous	FSP	✓	-	-	-	✓	✓	-	✓	Dynamic Deterministic	Dynamic Programming
New (1975)	Aircraft	Heterogeneous	FCP	-	✓	-	-	-	✓	-	✓	Dynamic Deterministic	Linear Programming
Parikh (1977)	Vehicle	Homogeneous	FSP	-	✓	-	-	-	-	-	-	Continuous Stochastic	Analytical Modeling
Williams and Fowler (1980)	Vehicle	Homogeneous	FSP	-	-	-	-	-	✓	-	-	Static Stochastic	Simulation
Etezadi and Beasley (1983)	Vehicle	Heterogeneous	FCP	-	✓	-	✓	-	✓	-	✓	Dynamic Deterministic	Mixed-Integer Programming
Gheysens et al. (1984)	Vehicle	Heterogeneous	FCP	-	✓	-	✓	-	-	-	-	Static Deterministic	Heuristic
Turnquist and Jordan (1986)	Container	Homogeneous	FSP	-	✓	✓	-	-	✓	-	-	Continuous Stochastic	Algorithm
Avramovich et al. (1982)	Truck	Heterogeneous	FCP	-	-	-	-	-	✓	-	✓	Dynamic Deterministic	Linear Programming
Couillard and Martel (1990)	Truck	Heterogeneous	FCP	-	-	-	-	✓	✓	-	✓	Dynamic Stochastic	Heuristic
Klincewicz et al. (1990)	Vehicle	Homogeneous	FSP	-	✓	-	✓	✓	✓	-	✓	Dynamic Stochastic	Algorithm
Beaujon and Turnquist (1991)	Vehicle	Homogeneous	FSP	-	✓	✓	-	✓	-	-	✓	Dynamic Stochastic	Algorithm
Du and Hall (1997)	Vehicle	Homogeneous	FSP	-	✓	✓	-	-	-	-	✓	Dynamic Stochastic	Programming
Köchel (1997)	Vehicle	Homogeneous	FSP	-	✓	✓	-	-	-	-	-	Static Deterministic	Analytical Modeling
Redmer et al. (2000)	Vehicle	Heterogeneous	FCP	-	-	-	-	-	-	✓	-	Continuous Stochastic	Analytical Modeling
Zhao et al. (2001)	Vehicle	Heterogeneous	FCP	✓	✓	-	-	✓	-	-	✓	Dynamic Deterministic	Dynamic Programming

Table 6.2 Problem and modelling characteristics of fleet sizing and composition problems in unimodal transportation systems (Continued)

Article	Resource Type	Fleet Structure	Fleet Problem	Load Allocation	Fleet Allocation	Empty Repositioning	Vehicle Routing	Outsourcing	Fleet Expansion/Reduction	Multi Objective	Multi Period	Problem Characteristics	Solution Methodology
Imai and Rivera (2001)	Container	Homogeneous	FSP	-	✓	✓	-	✓	-	-	-	Continuous	Simulation
Köchel et al. (2003)	Vehicle	Homogeneous	FSP	-	✓	✓	-	-	-	-	-	Deterministic	Modeling
List et al. (2003)	Vehicle	Heterogeneous	FCP	-	✓	-	-	-	✓	✓	✓	Static	Simulation
Koo et al. (2004)	Vehicle	Homogeneous	FSP	-	✓	✓	✓	-	-	-	-	Deterministic	Optimization
Wu et al. (2005)	Truck	Heterogeneous	FCP	✓	✓	✓	-	-	✓	-	✓	Dynamic	Stochastic
Vis et al. (2005)	Vehicle	Homogeneous	FSP	-	✓	✓	-	-	-	-	-	Stochastic	Programming
Papier and Thonemann (2008)	Vehicle	Heterogeneous	FCP	-	-	-	-	✓	-	-	-	Static	Meta-Heuristic
Qiuping et al. (2009)	Ship	Heterogeneous	FCP	-	✓	-	✓	-	✓	-	✓	Deterministic	Algorithm
Sayarshad and Ghoseiri, (2009)	Rail-Car	Homogeneous	FSP	-	✓	✓	-	-	✓	-	✓	Dynamic	Mixed-Integer
Dong and Song (2009)	Container	Homogeneous	FSP	-	✓	✓	-	-	-	-	✓	Deterministic	Programming
Sayarshad and Moghaddam (2010)	Rail-Car	Homogeneous	FSP	-	✓	✓	-	-	✓	-	✓	Dynamic	Meta-Heuristic
Cheon et al. (2012)	Rail-Car	Heterogeneous	FCP	-	-	-	-	✓	✓	-	✓	Stochastic	Algorithm
Redmer et al. (2012)	Tanker	Heterogeneous	FCP	✓	✓	-	-	-	-	-	-	Dynamic	Mixed-Integer
Carbajal et al. (2013)	Truck	Homogeneous	FSP	-	✓	✓	-	✓	-	-	-	Deterministic	Programming
Roy et al. (2013)	Truck	Homogeneous	FSP	-	-	-	-	-	-	-	-	Static	Meta-Heuristic
Koç et al. (2014)	Vehicle	Heterogeneous	FCP	-	-	-	✓	-	-	-	-	Continuous	Analytical
												Stochastic	Modeling
												Static	Meta-Heuristic
												Deterministic	Algoritm

FSP – Fleet Sizing Problem

FCP – Fleet Composition Problem

6.2.2 Literature Review on Fleet Planning in Intermodal Transportation Systems

Although there are many studies on the fleet sizing and composition, empty vehicle repositioning, load/freight planning, vehicle allocation and vehicle routing problems in unimodal transportation systems; there is still a few researches in the literature on fleet planning problems in intermodal transportation systems. In detail, most of the researches in intermodal transportation systems focused on the load/freight planning, container management, mode selection, transportation service and network design problems etc. (Guelat et al. 1990; Bierwirth et al., 2012; Meisel et al., 2013). Caris et al. (2008) also highlighted that truck and trailer fleet size optimization and managing the empty truck/trailer repositioning are vital issues in intermodal transportation systems and still need to be investigated. A brief summary of the articles which focused on freight transportation planning, fleet sizing and composition, empty container repositioning problems in intermodal transportation can be given as follows:

A normative model based on network representation was first presented by Guelat et al. (1990) for a multi-product and multi-mode strategic network assignment and freight planning problem in a Brazil transportation system. The multi-mode network involves nodes, links and modes which accounts for all the physical movements possible on the present infrastructure. Gauss Seidel linear approximation algorithm was employed to exploit the multi-product aspects of the model and minimize the intermodal transfer costs by shortest path algorithm. An integrated fleet planning model was formulated by Lin and Ma (1999) for a multi-modal transportation network where both ground and air express services are available. In addition to determine the best fleet size, freight routes can also be obtained from the solution of that model. The model was solved under maximum service time constraints of different fleet types so as to minimize the total fixed vehicle and variable routing costs. Since the large number of spoke combinations for each fleet type, fleet planning problem was decomposed into two separate integer programs. Then, an exact solution approach including a degree and time constrained minimum spanning tree algorithm namely Kruskal greedy algorithm was implemented. The proposed model was verified on real-life case study in the largest freight delivery carrier of Taiwan. According to the results, integrated fleet requires one less vehicle and provides approximately 16.7% cost

saving against to the two separate fleets. Choong et al. (2002) focused on the empty container management problem in intermodal transportation networks at tactical level and developed an integer programming formulation of the problem. The effects of the length of the planning horizon on mode selection and empty container repositioning were also analyzed. However, they only considered single type of resource namely containers in their proposed model.

A hybrid and iterative algorithmic solution procedure was developed by Jansen et al. (2004) for automatic and operational planning of transport orders in multi-modal transportation environments. In order to provide a cost-efficient transportation plan, various system constraints related to timing of orders, capacity of transport and processing limitations at freight centers, empty container repositioning etc. were taken into account in an integrated way. For solution of such a general complex problem, they decomposed it into the some important sub-problems which contain multi-modality choice, repositioning, order combination, order planning and plan improvement etc. Besides, sequence of tours on a truck was also checked for each step of the proposed iterative approach. In detail, after the assignment of orders to transport modes and planning of empty containers, order planning was performed with the help of a constructive heuristic and finally better plans were achieved by applying a local search procedure. Wang and Wang (2007) also proposed an integer program depend on a dynamic deterministic single-commodity model for intermodal empty container repositioning problem of a road shipping company. The road, rail and marine transportation modes with their specific lower and upper transport capacities were included by the proposed model. Supply and storage capacities of the ports and depots were also considered while minimizing the empty container distribution costs between the ports, suppliers and demand points. A simulation optimization approaches based on genetic algorithm, golden section and simulated annealing algorithms were developed by Dong and Song (2012) to determine the appropriate container fleet size and empty container repositions in an intermodal transportation network. It was also highlighted by the authors that container fleet sizing is relatively limited in the literature with regard to vehicle fleet sizing because of some differences in problem characteristics such as multiple transportation modes and different load units. They also took into account the uncertainties such as random customer demands and

stochastic inland transport times. The influence of variability related to inland transit times on container fleet size was also investigated via various simulation experiments.

As previously mentioned in Chapter 5, mathematical programming models were developed by Bierwirth et al. (2012) and Meisel et al. (2013) for tactical intermodal freight transportation planning and service selection problems. In detail, integrated production and transportation planning activities were handled by these models from the perspective of a production company. Opposite to the formerly given studies, they did not deal with the fleet sizing/composition and empty vehicle repositioning problems since the examined problem belongs to a production firm rather than a logistics company. Moreover, they just considered the combined rail and road distribution networks without maritime logistics activities. Furthermore, resource managements subjects like resource allocation, empty vehicle repositioning, inventory levels of trucks/trailers at different locations, train/ship scheduling etc. were out of scope of these papers. A two-stage heuristic was developed by Nossack and Pesch (2013) to solve a truck scheduling problem composed of empty container assignment and truck routing problems in an intermodal transportation network. They also presented a new mathematical formulation of the problem depending upon a full-truckload pickup and delivery problem including time windows. Since the NP-hard nature of the examined truck scheduling problem, a route construction heuristic was employed so as to obtain an initial feasible solution in the first stage of the proposed heuristic. In detail, at this first stage, (i) pairing pickup and delivery requests, (ii) sequencing these pickup and delivery pairs, (iii) assignment of start and end depots to the sequences and finally (iv) assignment of start and end times to the routes were carried out. Then, the provided solution was improved in the second stage by utilizing an ejection chain heuristic which is ability to perform multiple neighborhood changes within one iteration.

A mixed-integer linear programming formulation was given by Fazi et al. (2013) for mode allocation and heterogeneous fleet vehicle routing problems in a container supply chain. In fact, the proposed mathematical model aims at allocating containers to the available vehicle fleet by considering the cost and service level criteria. Their model was also tested on a real-life case study at an inland terminal in the Netherlands.

In order to solve the large scaled real-world problem instances, a Markov chain Monte Carlo heuristic with variable neighborhood search algorithm was implemented. It was also highlighted that development of decision support systems for this kind of operational problem may provide cost and time efficient plans for the logistic planners. An extensive bi-level freight transportation optimization model was developed by Zhang et al. (2015) for integrated infrastructure network, service network and regulatory policy design problems. Actually, the proposed model jointly incorporated the multi-actor, multi-commodity and multimodal large sized transportation network to achieve minimal network costs and CO₂ emissions. At the upper-level, optimal network performances and policy measures were investigated in terms of governments by minimizing the total network costs. On the other hand, multi-commodity flow was assigned to the intermodal transportation network at the lower level problem. A derivative all-or-nothing algorithm which mainly depends on the Dijkstra's shortest path method and genetic algorithm were utilized as solution methodologies. Crainic et al. (2015) formulated a mixed-integer programming model for design and management of freight distribution in a multi-echelon dry-port-based intermodal system. In other words, their optimization model handled some tactical planning issues such as service network design, optimal schedules and routes for the available vehicle fleet. Indeed, the vehicle fleet size and composition were used as input problems within the proposed tactical planning model. Similar to the many former studies on network design, time-space network representation of the stated problem was realized. A deterministic mixed-integer mathematical programming model was developed by Baykasoğlu et al. (2015) for strategic and tactical fleet planning problems in intermodal transportation networks. In their model, both of the importation and exportation of freights were taken into account to satisfy the customer transport demands in Europe. In order to balance import and export load flows, they handled the multi-mode load planning, fleet sizing/composition and empty vehicle repositioning problems in an aggregated way.

Similar with the previous sub-section, all of the above researches dealt with intermodal freight transportation can be categorized with respect to problem/modelling features as presented in Table 6.3. An overview of the articles which concentrated on the fleet planning problems in unimodal and intermodal transportation systems can be summarized in Figure 6.4 in terms of decision levels and different solution techniques.

Table 6.3 Problem and modelling characteristics of fleet/freight planning problems in intermodal transportation systems

Article	Resource Type	Fleet Structure	Fleet Problem	Freight Planning	Fleet Allocation	Empty Repositioning	Vehicle Routing	Outsourcing	Fleet Expansion/Reduction	Multi Objective	Multiple Actor	Multi Period	Problem Characteristics	Solution Methodology
Guelat et al. (1990)	Train	Homogeneous	-	✓	-	-	-	-	-	-	-	-	Static Deterministic	Heuristic Algorithm
Lin and Ma (1999)	Aircraft, Truck	Homogeneous	FSP	✓	✓	-	-	-	-	-	-	-	Static Deterministic	Integer Programming
Choong et al. (2002)	Container	Homogeneous	-	-	-	✓	-	✓	✓	-	-	-	Static Deterministic	Integer Programming
Jansen et al. (2004)	Truck	Heterogeneous	-	✓	✓	✓	-	-	-	-	-	-	Static Deterministic	Heuristic Algorithm
Wang and Wang (2007)	Container	Homogeneous	-	✓	-	✓	-	-	-	-	-	✓	Static Deterministic	Integer Programming
Bierwirth et al. (2012)	Train	Homogeneous	-	✓	-	-	-	-	-	-	-	-	Static Deterministic	Mixed-Integer Programming
Dong and Song (2012)	Container	Homogeneous	FSP	-	-	✓	-	-	✓	-	-	-	Dynamic Stochastic	Simulation Optimization
Meisel et al. (2013)	Train	Homogeneous	-	✓	-	-	-	-	-	✓	-	-	Static Deterministic	Heuristic Algorithm
Fazi et al. (2013)	Container	Heterogeneous	-	✓	✓	-	✓	-	-	-	-	-	Static Deterministic	Heuristic Algorithm
Nossack and Pesch (2013)	Truck	Homogeneous	FSP	-	✓	✓	✓	-	-	-	-	-	Static Deterministic	Heuristic Algorithm
Zhang et al. (2015)	Truck	Homogeneous	FSP	✓	-	-	-	-	-	✓	✓	-	Static Deterministic	Metaheuristic Algorithm
Crainic et al. (2015)	Flat car	Homogeneous	-	✓	✓	-	✓	-	-	-	-	-	Static Deterministic	Mixed-Integer Programming
Baykasoğlu et al. (2015)	Truck/Trailer	Heterogeneous	FSP	✓	✓	✓	-	✓	-	-	✓	✓	Static Deterministic	Mixed-Integer Programming
Proposed model	Truck/Trailer	Heterogeneous	FSP	✓	✓	✓	-	✓	✓	✓	✓	✓	Static Fuzzy & Stochastic	Mixed-Integer Programming

FSP – Fleet Sizing Problem

Freight Planning – Loads are allocated to the transportation modes and/or routes

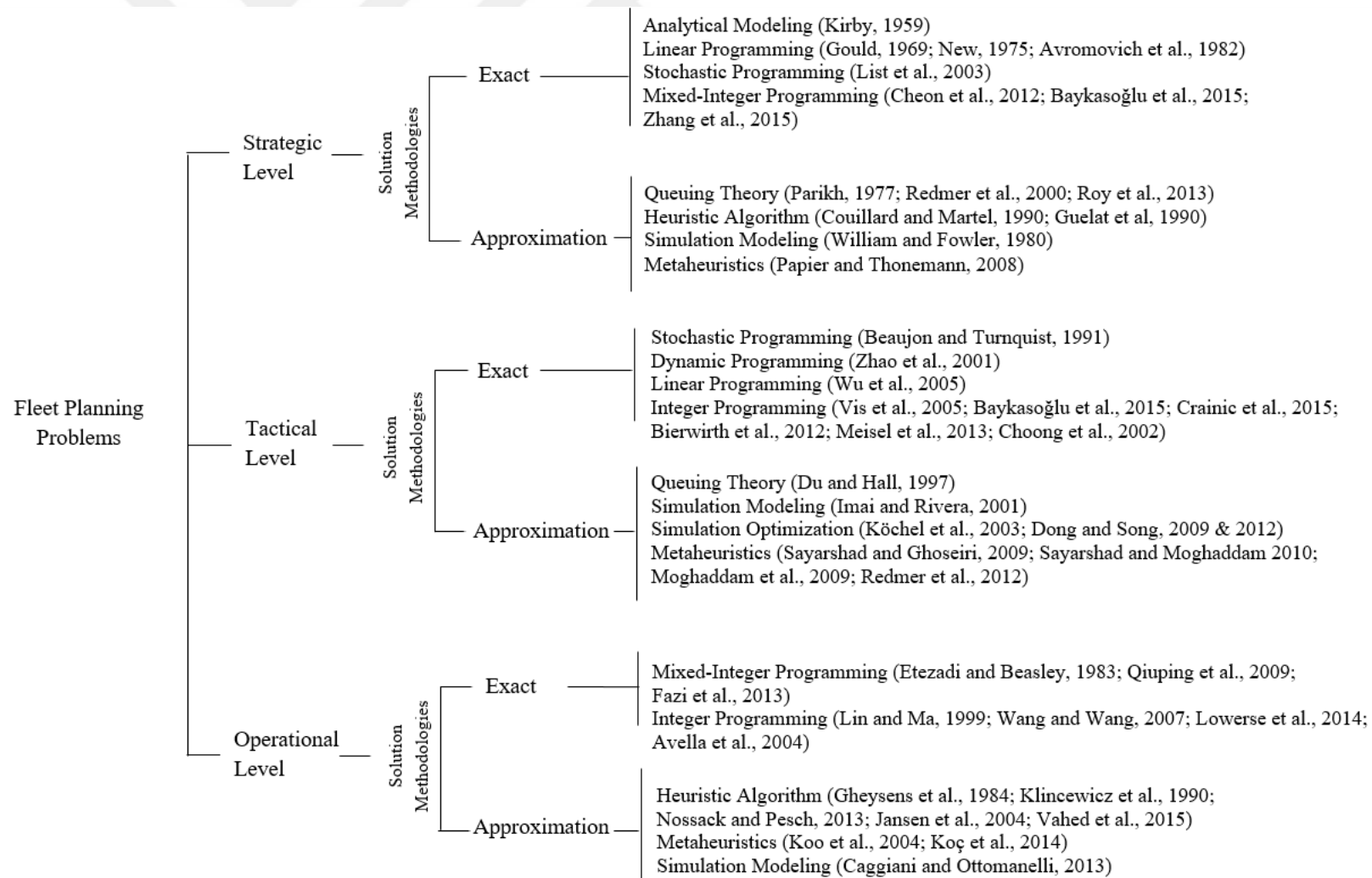


Figure 6.4 Different solution methodologies to unimodal and intermodal fleet planning problems at different decision levels

6.3 A Mathematical Programming Based Decision Support System framework for Intermodal Fleet Planning

In this section, a decision support system (DSS) framework based on a novel fuzzy and stochastic mathematical programming model is introduced for a multi-objective, multiple resource and multi-period intermodal fleet planning problem. As persistently emphasized by the current studies in the literature, development of a DSS is quite needed to support the strategic, tactical and operational level fleet planning activities of different actors in intermodal transportation systems. For this reason, an architecture for a DSS which covers the proposed holistic intermodal fleet planning model is presented in Figure 6.5. As is the case with most other DSS, the proposed system is also composed of four main components. In the scope of this thesis, we primarily focused on the model component and it is extensively elaborated as in the followings:

(i) Data component: This part of the DSS consists of a database and information communication technology which collect, store and process the crisp and imprecise data as inputs of the proposed mathematical programming model.

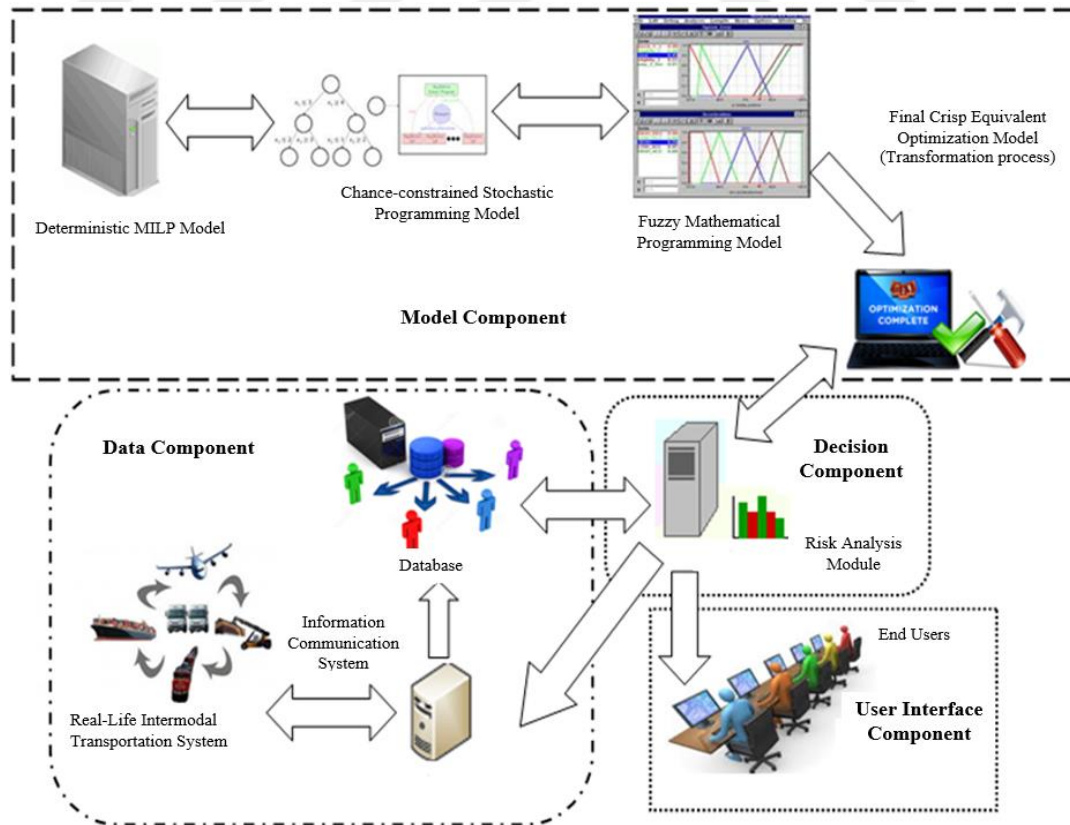


Figure 6.5 Main components of the proposed decision support system for intermodal fleet planning

This component maintains necessary subjective information (pessimistic, most likely and optimistic values of fuzzy parameters) from the company experts, external information (initial truck/trailer inventories at different locations) from the intermodal transportation environment and organizational information (monthly import/export freight demands) from the logistics company's database and data warehouses.

(ii) User interface: This part of the DSS is required for direct contract of the end users. In other words, effective and efficient usage and operation of the decision support system by the users can be achieved by this component. The graphical user interface management system of the proposed DSS is able to visualize the freight/fleet plans, load/fleet allocation, monthly business volume and trips of Ro-Ro vessels/block trains on web-based logistics maps.

(iii) Decision component: This part of the DSS is able to present various solutions to the company experts for freight and fleet planning activities under different uncertainty levels and risk attitudes. This component is also needed for obtaining just cost-oriented, customer-focused or environmental friendly fleet plans and also compromise plans for these conflicting objectives. Furthermore, this component also contains the risk analysis module which can provide risky and risk-free fleet plans in accordance with different feasibility degrees of model constraints under various demand scenarios.

(iv) Model component: This modeling and optimization component includes the proposed mixed-integer mathematical programming model of the present intermodal fleet planning problem and the relevant fuzzy & stochastic solution approaches to transform the problem into a crisp equivalent form. In the modeling phase, the deterministic mixed-integer programming (MIP) model is initially developed with four fleet planning phases. The proposed intermodal fleet planning framework with four different phases can be visualized as in Figure 6.6. In detail, multi-mode load planning or intermodal freight transportation planning model is first proposed afterwards extended by incorporating the truck/trailer fleet size and composition, loaded and empty truck/trailer movements, truck/trailer inventories on the logistics network and fleet expansion and reduction decisions. Briefly, while developing the deterministic MIP model of the intermodal fleet planning problem, there are four substantial model development phases which can be shown by the following Figure 6.7.

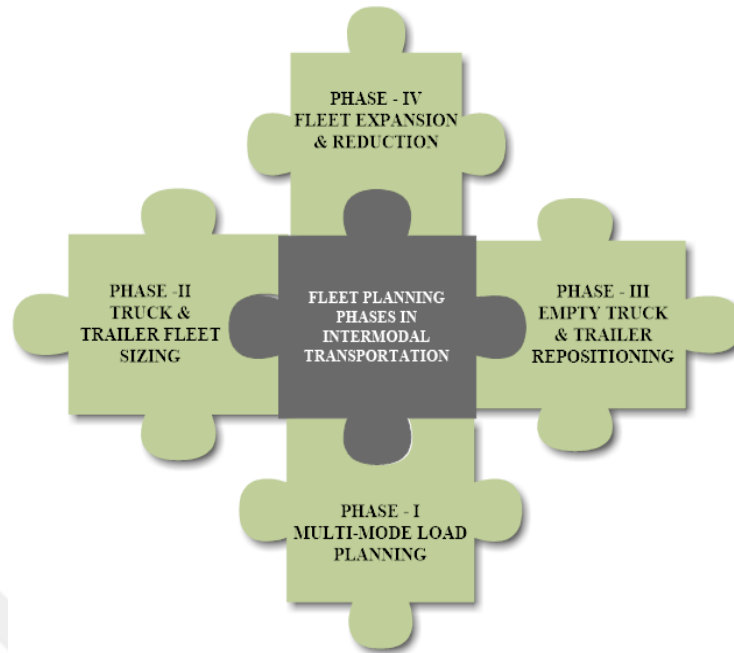


Figure 6.6 The proposed intermodal fleet planning framework with four different phases

Therefore, outputs of the proposed MIP model can be summarized as follows:

- Optimal mode and routes of the freights,
- Optimal size and composition of the resources,
- Optimal resource allocations and inventories,
- Optimal empty vehicle reallocations (repositions),
- Optimal purchasing, selling and outsourcing decisions.

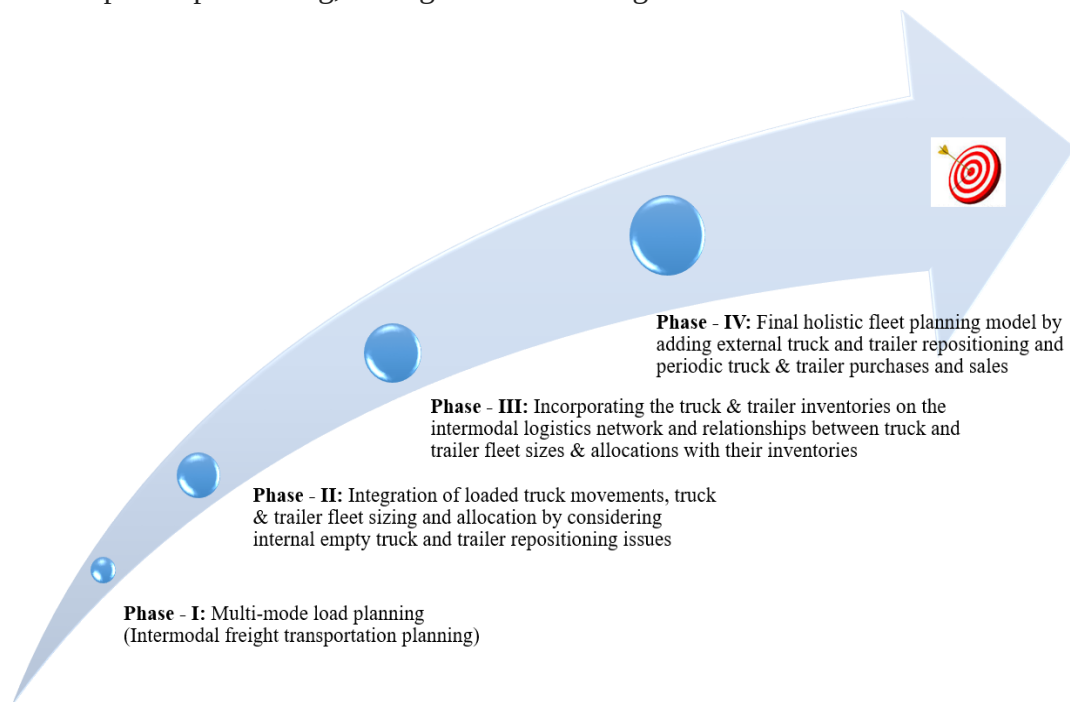


Figure 6.7 Model development phases for the deterministic intermodal fleet planning problem

In fact, the proposed intermodal fleet planning framework which addressed all of the aforementioned planning problems is realized incrementally in four phases. All of the interrelated intermodal transportation planning problems are gathered at the last phase and solved by the corresponding MIP model. In detail, each phase may contain some outputs of the previous phases and generate the inputs of the latter phases. However, it should be noted here that these phases do not constitute an iterative process. In other words, the final holistic fleet planning model incorporates all of the inputs and outputs belonging to the previous phases. After fulfilment of this last phase, the proposed MIP model constitutes the basis of the DSS which is developed for the intermodal fleet management in EKOL Logistics Inc. The structure and characteristics of the first phase namely multi-mode load planning or intermodal freight transportation planning can be summarized by the following Figure 6.8. This phase of the intermodal fleet planning framework is extensively discussed in the previous Chapter 5 of this thesis. For this reason, the subsequent phases are the main focus of this chapter instead of this first model development phase. Hence, only the inputs and outputs of this first phase are presented in this chapter to avoid the duplications.

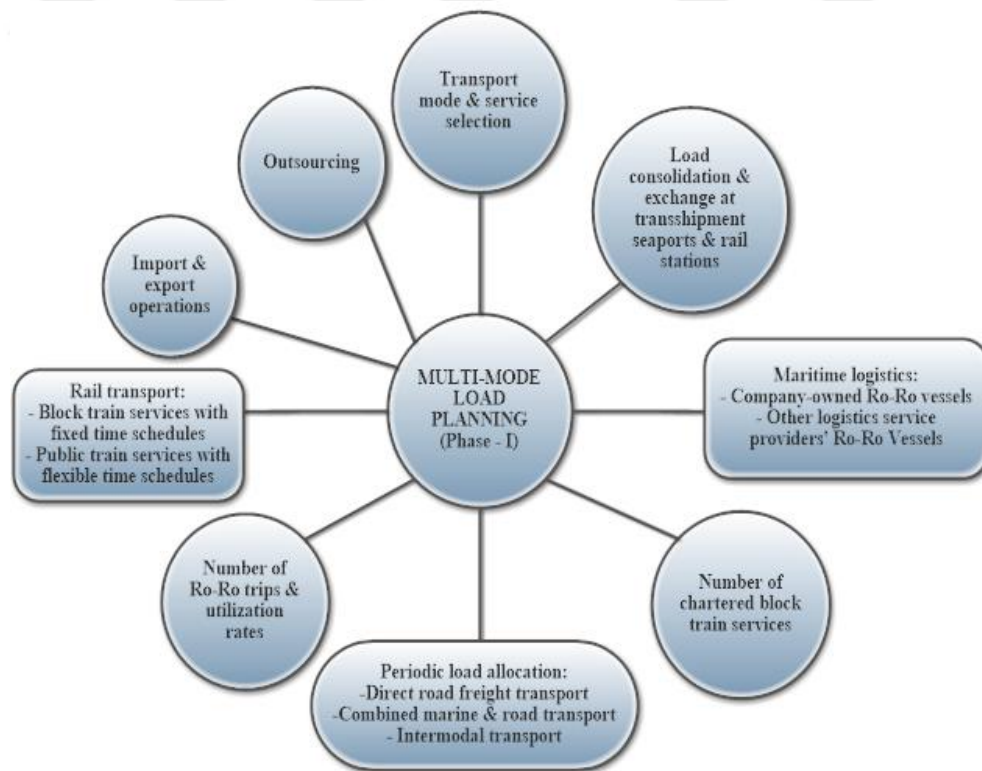


Figure 6.8 Characteristics of phase-I: Multi-mode load planning or intermodal freight transportation planning problem

Inputs of Phase-I: Multi-mode load or intermodal freight transportation planning:

- Marine transportation costs for import/export operations by company owned Ro-Ro vessels and other logistics service providers' Ro-Ro vessels,
- Railway transport costs per block train chartered for importation/exportation,
- Railway transport costs for import/export operations by public trains,
- Road freight transportation cost per km of per trailer by European or Turkish plated trucks for both importation and exportation,
- Outsourcing cost per transportation unit (trailer or container) of import/export operations between seaports in Turkey and order countries,
- Random import/export freight demands of order countries at each month,
- Transportation capacities per trip of company-owned Ro-Ro vessels for importation/exportation,
- Maximum number of marine trips at each month that can be performed by the company-owned Ro-Ro vessels for importation/exportation,
- Transport capacity of per block train service for import/export operations,
- Maximum number of available block train services at each month for importation/exportation,
- Lower bounds on the number of block train services at each month for import/export operations,
- Lower bounds on the utilization rates of the company-owned Ro-Ro vessels for import/export operations,
- Road travel distances between seaports in Turkey and order countries; seaports in Europe and order countries; railway terminals and order countries,
- Marine travel distances among the seaports and railway travel distances among the railway stations,
- The amounts of CO₂ emission by marine, rail and road freight transportations.

Outputs of Phase-I: Multi-mode load or intermodal freight transportation planning:

- Transportation mode selection and load allocation to different transportation services, i.e., direct road freight transport, combined marine and road freight transport, intermodal transportation and outsourcing option,

- Import/export transportation quantities shipped by the company-owned Ro-Ro vessels at each month,
- Import/export transportation quantities shipped by the other logistics service providers' Ro-Ro vessels,
- The required number of marine cruises by company-owned Ro-Ro vessels at each month for importation/exportation,
- Utilization rates of the company-owned Ro-Ro vessels at each month for import/export transportation operations,
- The required number of chartered block train services at each month for importation/exportation,
- Import/export transportation quantities shipped by public trains at each month,
- Import/export transportation quantities transferred by the transshipment seaports, i.e., Lavrion port,
- Import/export transportation quantities transferred by the transshipment railway terminals, i.e., Cologne station.

The structure and characteristics of the second model development phase which is called as truck/trailer fleet size optimization, fleet composition and fleet allocation can be shown by the below Figure 6.9.

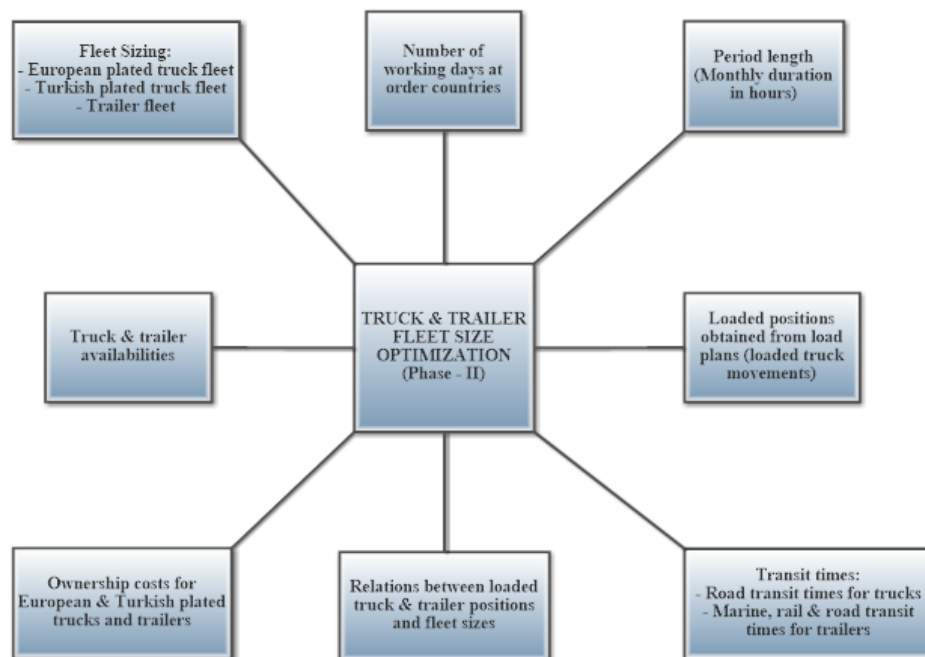


Figure 6.9 Characteristics of phase-II: Truck and trailer fleet size optimization and fleet allocation

In contrast to the existing studies in the literature, both of the truck and trailer fleet size optimization is intended in the scope of the proposed DSS. Fleet size of vehicles is determined for each time period by considering the loaded truck/trailer positions, empty repositions, transit times and length of the period and truck/trailer availabilities. In detail, quantities of loaded truck positions can be obtained from the solution of the first phase, i.e., multi-mode load planning model. In addition to these loaded truck movements, road-marine-rail transit times between the origin and destination pairs, the monthly duration (in hours) and the percent of time for truck/trailer availabilities are needed so as to determine the appropriate fleet size. Composition of the truck fleet is also determined by considering the different types of identification plates such as European and Turkish plated vehicles. Actually, because of the cabotage laws in Europe, this is an important issue for realizing the loaded and empty truck movements with different types of plates. An appropriate fleet sizing/composition and fleet allocation can also provide minimal empty truck/trailer repositioning. The inputs and outputs of this second phase can be given as follows:

Inputs of Phase-II: Truck and trailer fleet size optimization and fleet allocation:

- All of the inputs of the first phase: multi-mode load planning,
- Monthly fixed ownership costs per European/Turkish plated trucks and trailers,
- Internal empty truck and trailer repositioning costs per kilometer,
- Road transit times for truck fleet sizing,
- Road, marine and rail transit times for trailer fleet sizing,
- The duration or period length (in hours) of a monthly time period,
- The number of working days in each order country at each month,
- Availabilities or percent of time for European/Turkish plated trucks and trailers at each month.

Outputs of Phase-II: Truck and trailer fleet size optimization and fleet allocation:

- The number of loaded truck movements (in positions) by European/Turkish plated trucks within Europe and between Turkey and order countries,
- European/Turkish plated truck fleet size requirements on each route of road transport network,

- General trailer fleet size required by all the modes of transport on the intermodal logistics network,
- Relationship and connection between the load plans and fleet sizes,
- Relationship between loaded truck/trailer positions and fleet sizes,
- Internal empty truck and trailer repositions,
- Truck and trailer fleet allocation by achieving minimal internal empty truck and trailer repositions.

For better understanding of fleet sizing, fleet allocation and internal empty truck repositioning concepts, an illustrative numerical example is presented as it can be seen from Figure 6.10. If the trucks can be used more than once in a specific time period, parameters related to travel times, length of the planning period and availability of the sources will be essential as well as the loaded truck positions in fleet size optimization.

Suppose that the number of loaded truck movements between the nodes i and j are 100 and 70 positions, respectively. The travel time between these nodes is 100 time units per position. The planning horizon is set to one month and there are 25 working days available at a month. In fact, each truck can perform 6 trips among these nodes throughout the planning period. Moreover, it is assumed that trucks are always ready for transportation operations or available 100% percent at a given time period. In this case, minimum number of required trucks at arcs (i, j) and (j, i) can be calculated by using the following formulas (6.1) and (6.2) (Baykasoğlu et al., 2015):

$$Truck_{ij} + Truck_{ji} \geq 2 * \left\lceil \frac{\max \{Time_{ij} * Position_{ij}, Time_{ji} * Position_{ji}\}}{Period Length * Truck Availability} \right\rceil = \quad (6.1)$$

$$\frac{Time_{ij} * Position_{ij} + Time_{ji} * Position_{ji} + |Time_{ij} * Position_{ij} - Time_{ji} * Position_{ji}|}{Period Length * Truck Availability}$$

$$Period Length = Number of working days * duration (in hours) \quad (6.2)$$

According to the above formulations, the total number of required truck fleet size at nodes i and j can be computed as follows:

$$Truck_{ij} + Truck_{ji} \geq (70 * 100 + 100 * 100 + |70 * 100 - 100 * 100|) / 600 * 1.0 \approx 34 \quad (6.3)$$

The truck fleet size will change in case of revisions in load plans and the values of the relevant parameters are varied. After determining the appropriate truck fleet size,

allocation of these trucks between the nodes i and j is so vital in terms of the solution quality. In detail, the amount of empty truck repositions is directly related to the initial positions of these trucks. In other words, the total number of 34 trucks should be allocated accurately to the routes among these nodes or arcs (i, j) and (j, i) so as to transport the planned import/export freights within the given time period. Moreover, the fleet allocation is very essential due to its significant effects on the total transportation costs. Because, huge number of empty truck repositions may arise when the truck fleet is not allocated effectively among the different locations. Therefore, inappropriate fleet allocation causes larger internal empty truck repositions with its associated costs. The required number of empty truck repositions between the nodes i and j can be determined by the following Equations (6.4) and (6.5):

$$Reposition_{ji} \geq Position_{ij} - Position_{ji} - Truck_{ij} \quad (6.4)$$

$$Reposition_{ij} \geq Position_{ji} - Position_{ij} - Truck_{ji} \quad (6.5)$$

Finally, after the fleet allocation and empty truck repositions, periodic truck inventories at the end of the planning period can be formulated for the nodes i and j as in Equations (6.6) and (6.7), respectively. Furthermore, physical representation of fleet allocation and impact of the allocation decisions on solution quality can be clarified by following three cases, i.e., perfect, poor and comparatively better allocations.

$$Inventory_i = Truck_{ij} - Position_{ij} + Position_{ji} + Reposition_{ji} - Reposition_{ij} \quad (6.6)$$

$$Inventory_j = Truck_{ji} - Position_{ji} + Position_{ij} + Reposition_{ij} - Reposition_{ji} \quad (6.7)$$

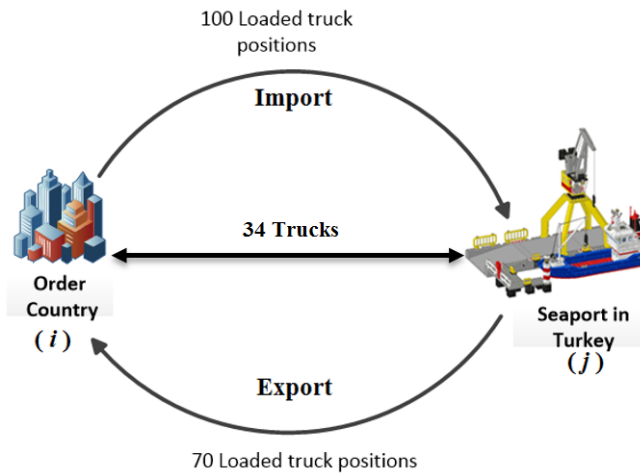


Figure 6.10 An illustrative example for fleet sizing and allocation by considering empty repositions

Case-1: A perfect fleet allocation without any empty truck reposition: 30 trucks are available on arc (i, j) and 4 trucks on arc (j, i) at the beginning of the planning horizon.

$$Reposition_{ji} \geq 100 - 70 - 30 = 0 \quad Inventory_i = 30 - 100 + 70 + 0 - 0 = 0$$

$$Reposition_{ij} \geq 70 - 100 - 4 = -34 \quad Inventory_j = 4 + 100 - 70 + 0 - 0 = 34$$

Table 6.4 An illustrative example for perfect fleet allocation

Truck inventory at Order Country (i)	Trip-0 Number of import positions	Truck inventory at Seaport in Turkey (j)
30	→ 100	
Number of export positions		
	70 ←	4
Truck inventory at Order Country (i)	Trip-1 Number of import positions	Truck inventory at Seaport in Turkey (j)
4	→ 70	
Number of export positions		
	66 ←	30
Truck inventory at Order Country (i)	Trip-2 Number of import positions	Truck inventory at Seaport in Turkey (j)
30	→ 66	
Number of export positions		
	36 ←	4
Truck inventory at Order Country (i)	Trip-3 Number of import positions	Truck inventory at Seaport in Turkey (j)
4	→ 36	0
Number of export positions		
0	32 ←	30
Truck inventory at Order Country (i)	Trip-4 Number of import positions	Truck inventory at Seaport in Turkey (j)
30	→ 32	0
Number of export positions		
0	2 ←	2 + 2
Truck inventory at Order Country (i)	Trip-5 Number of import positions	Truck inventory at Seaport in Turkey (j)
2	→ 2	0
Number of export positions		
0	0	30 + 2
Truck inventory at Order Country (i)	Trip-6 Number of import positions	Truck inventory at Seaport in Turkey (j)
0	0	0
Number of export positions		
0	0	32 + 2 = 34

In this case, it is obviously seen that there are no available trucks at node i and all of the trucks are accumulated at node j at the end of the planning horizon. In other words, all of the trucks will be terminated at node j whose incoming loaded truck positions are higher than node i . It is also clear that there is no need to reposition any empty truck among these nodes. Actually, the number of empty truck repositions is explicitly associated with initial truck positions. On the other hand, it should be emphasized here that truck inventory levels at the end of the planning period are directly related to the amounts of incoming and outgoing loaded truck positions.

Case-2: A poor fleet allocation which causes maximal empty truck reposition: 0 trucks are available on arc (i, j) and 34 trucks on arc (j, i) at the beginning of the planning horizon.

$$Reposition_{ji} \geq 100 - 70 - 0 = 30 \quad Inventory_i = 0 - 100 + 70 + 30 - 0 = 0$$

$$Reposition_{ij} \geq 70 - 100 - 34 = -64 \quad Inventory_j = 34 + 100 - 70 + 0 - 30 = 34$$

Table 6.5 An illustrative example for poor fleet allocation

Truck inventory at Order Country (<i>i</i>)	Trip-0 Number of import positions	Truck inventory at Seaport in Turkey (<i>j</i>)
0	100	
Number of export positions		
	70	34
Truck inventory at Order Country (<i>i</i>)	Trip-1 Number of import positions	Truck inventory at Seaport in Turkey (<i>j</i>)
34	100	
Number of export positions		
	36	0
Truck inventory at Order Country (<i>i</i>)	Trip-2 Number of import positions	Truck inventory at Seaport in Turkey (<i>j</i>)
0	66	
Number of export positions		
	36	34
Truck inventory at Order Country (<i>i</i>)	Trip-3 Number of import positions	Truck inventory at Seaport in Turkey (<i>j</i>)
34	66	0
Number of export positions		
0	2	0
Truck inventory at Order Country (<i>i</i>)	Trip-4 Number of import positions	Truck inventory at Seaport in Turkey (<i>j</i>)
0	32	0
Number of export positions		
0	2	34
Truck inventory at Order Country (<i>i</i>)	Trip-5 Number of import positions	Truck inventory at Seaport in Turkey (<i>j</i>)
Empty 30 + 2	32	0
Number of export positions		
0	0	2 Awaiting
Truck inventory at Order Country (<i>i</i>)	Trip-6 Number of import positions	Truck inventory at Seaport in Turkey (<i>j</i>)
0	0	0
Number of export positions		
0	0	32 + 2 = 34

In the present case, in order to conduct the loaded truck positions during the fifth trip from node *i* to node *j*, additional 30 empty truck repositions should be performed from node *j* to node *i*. Because of the fact that initial truck allocation may cause costly empty truck movements. It should be also highlighted here that since truck fleet size is taken as an integer number in the previous two cases (totally 34 trucks), the number of empty truck repositions and truck inventories will be integer as well. However, there are some idle/inactive trucks (32 idle trucks in case-1 and 2 idle trucks in case-2) which are awaiting at the node *j* in both cases to the end of the planning horizon. This is because of the integer fleet size restrictions. In order to overcome this drawback, except the loaded truck positions, all of the fleet size requirements, truck/trailer inventories, empty truck/trailer repositions, truck/trailer purchases and sales are represented by continuous decision variables. Thereby, the number of idle trucks or non-value added awaiting operations can be avoided.

Case-3: A comparatively better fleet allocation with relatively lesser empty truck repositions: 20 trucks are available at arc (*i*, *j*) and 14 trucks at arc (*j*, *i*) at the beginning of the planning horizon.

$$Reposition_{ji} \geq 100 - 70 - 20 = 10 \quad Inventory_i = 20 - 100 + 70 + 10 - 0 = 0$$

$$Reposition_{ij} \geq 70 - 100 - 14 = -44 \quad Inventory_j = 14 + 100 - 70 + 0 - 10 = 34$$

Table 6.6 An illustrative example for comparatively better fleet allocation

Truck inventory at Order Country (i)	Trip-0 Number of import positions	Truck inventory at Seaport in Turkey (j)
20	→ 100	
Number of export positions		
	70	← 14
Truck inventory at Order Country (i)	Trip-1 Number of import positions	Truck inventory at Seaport in Turkey (j)
14	→ 80	
Number of export positions		
	56	← 20
Truck inventory at Order Country (i)	Trip-2 Number of import positions	Truck inventory at Seaport in Turkey (j)
20	→ 66	
Number of export positions		
	36	← 14
Truck inventory at Order Country (i)	Trip-3 Number of import positions	Truck inventory at Seaport in Turkey (j)
14	→ 46	0
Number of export positions		
0	22	← 20

Truck inventory at Order Country (i)	Trip-4 Number of import positions	Truck inventory at Seaport in Turkey (j)
20	→ 32	
Number of export positions		
	2	← 14
Truck inventory at Order Country (i)	Trip-5 Number of import positions	Truck inventory at Seaport in Turkey (j)
Empty 10 + 2	→ 12	0
Number of export positions		
0	0	2 Awaiting
Truck inventory at Order Country (i)	Trip-6 Number of import positions	Truck inventory at Seaport in Turkey (j)
0	0	0
Number of export positions		
0	0	32 + 2 = 34

Similar to the previous cases, all of the trucks are accumulated at node j to the end of the planning horizon. The last case is comparatively better than the second poor fleet allocation case in terms of both number of empty truck repositions and idle trucks. The proposed holistic intermodal fleet planning model ensures perfect fleet allocations for both trucks and trailers under many different circumstances.

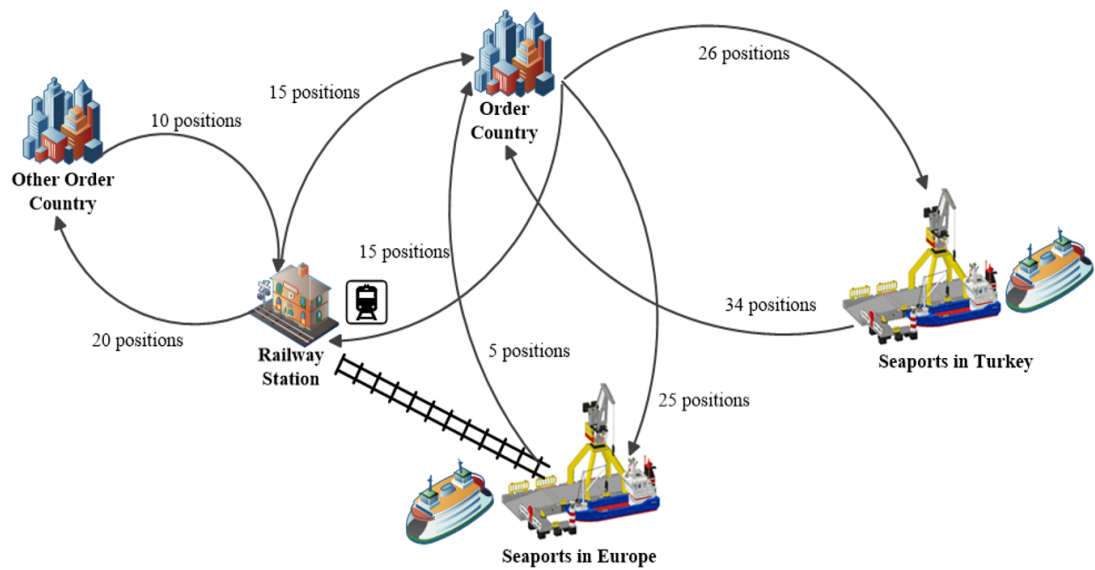


Figure 6.11 A more realistic illustrative example for intermodal fleet sizing and allocation

Apart from the trivial example given by Figure 6.10, a specific node (seaport, railway station, hub, order country etc.) on the intermodal logistics network has connections with many other nodes by directions of both importation/exportation as shown by Figure 6.11. Accordingly, almost all nodes have connections with each other in real-life intermodal transportation networks which makes the fleet sizing and allocation problems more complicated and difficult to solve. In this more realistic numerical example on intermodal fleet sizing and allocation, the values of travel times between each pair of nodes, number of working days at a month and truck availabilities are assumed to have same values with the previous trivial example. Similarly, each truck is able to realize 6 trips among these nodes throughout the planning horizon. According to Equations (6.1) and (6.2), total truck requirement will be 31 trucks on this intermodal transportation network. The perfect fleet allocation without any empty truck reposition can be achieved by initially allocating 10 trucks to the railway station, 13 trucks to the order country and 8 trucks to the seaport in Turkey, respectively. The optimal fleet size and allocation which minimize the empty truck repositioning can be shown by the following Figures 6.12 to 6.17 for each trip within the planning period. It should be noted here that along the first four trips, there is no idle trucks awaiting at the nodes on the network. However, the only 14 trucks of totally 31 trucks are active during the fifth trip and the remaining 17 trucks are awaiting at the seaport in Europe and order country. Similarly, 19 trucks are idle during the last trip and the remaining 12 trucks performed the loaded truck positions at the sixth trip.

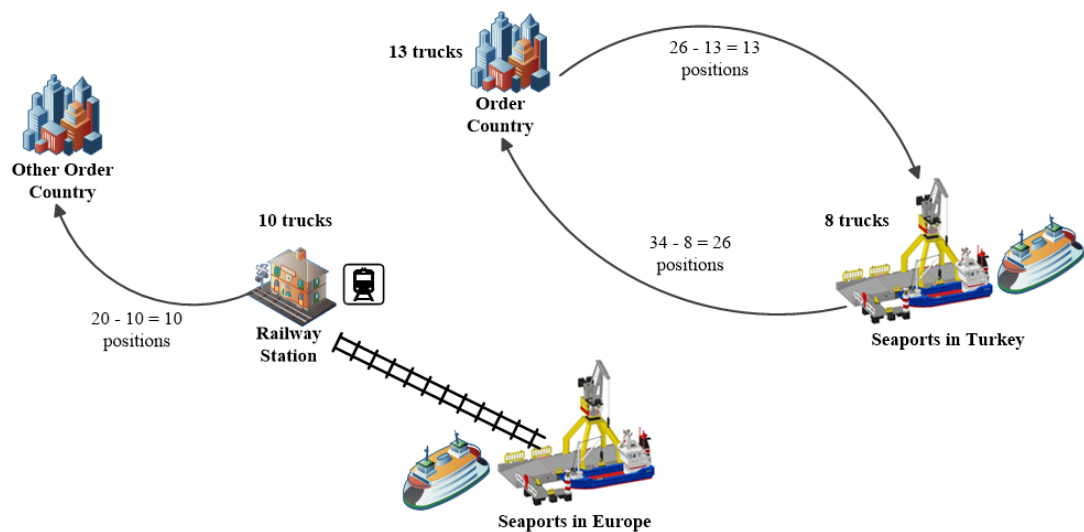


Figure 6.12 Initial fleet allocation and loaded truck positions along the first trip

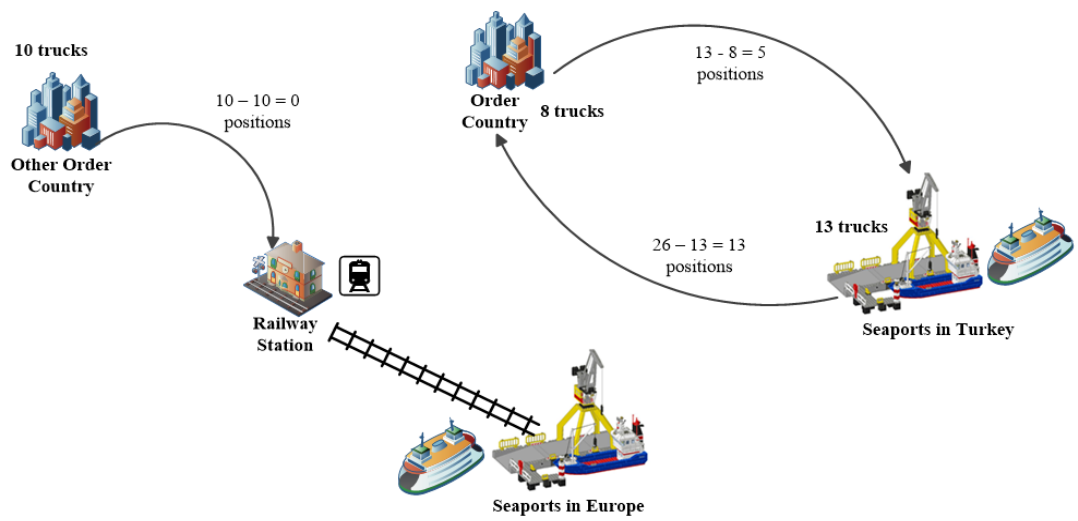


Figure 6.13 Truck inventories at the end of first trip and loaded truck positions along the second trip

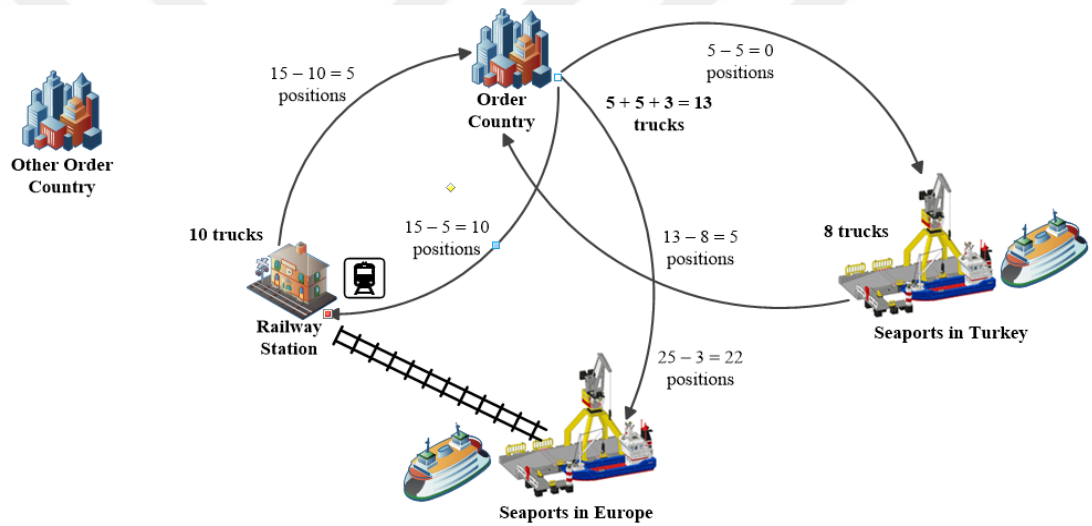


Figure 6.14 Truck inventories at the end of second trip and loaded truck positions along the third trip

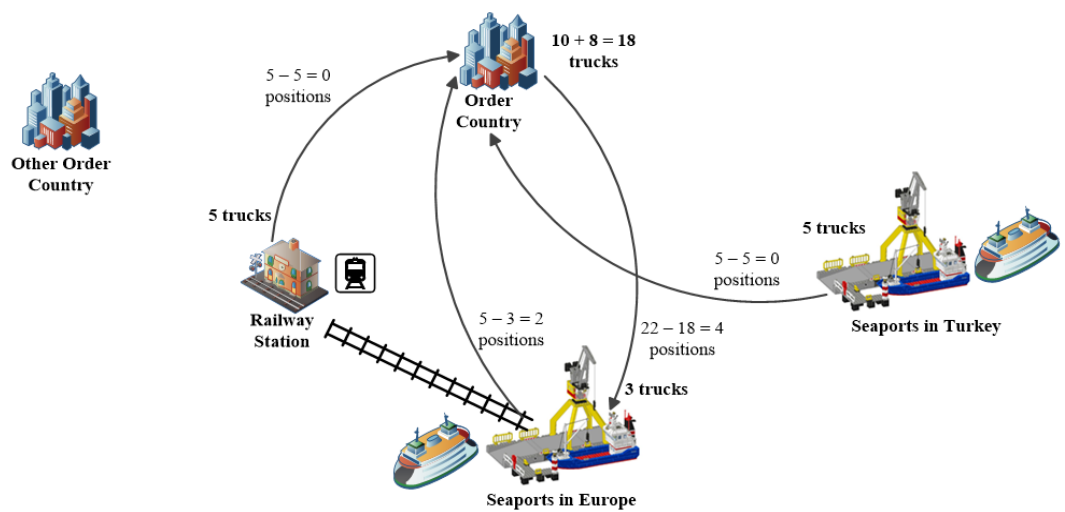


Figure 6.15 Truck inventories at the end of third trip and loaded truck positions along the fourth trip

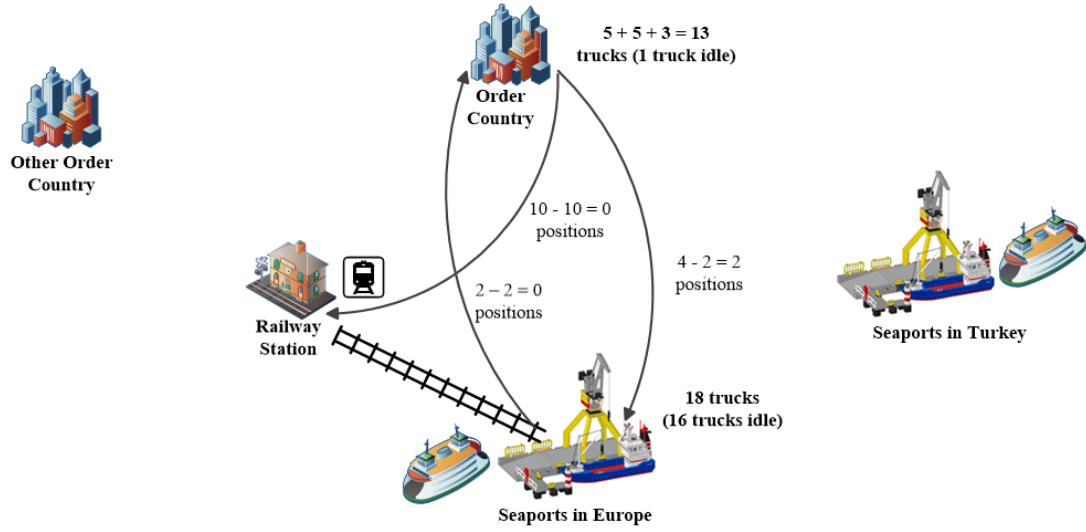


Figure 6.16 Truck inventories at the end of fourth trip and loaded truck positions along the fifth trip

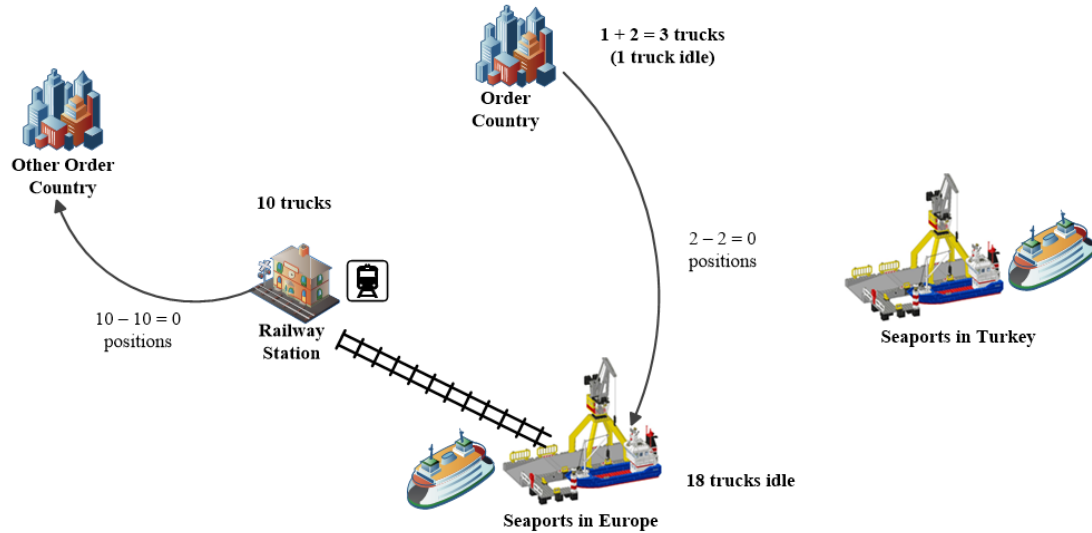


Figure 6.17 Truck inventories at the end of the fifth trip and loaded truck positions along the sixth trip

Finally, all of the loaded truck positions are completed without repositioning of empty vehicles at the end of the sixth trip. The final truck inventories at the end of the planning period will be 1 truck at the order country, 10 trucks at the other order country and 20 trucks at the seaport in Europe, respectively.

The structure and characteristics of the third and fourth model development phases which are called as *periodic truck/trailer inventories on the intermodal logistics network and fleet expansion/reduction decisions* and *external empty truck & trailer repositioning issues* can be displayed as in the following Figures 6.18 and 6.19.

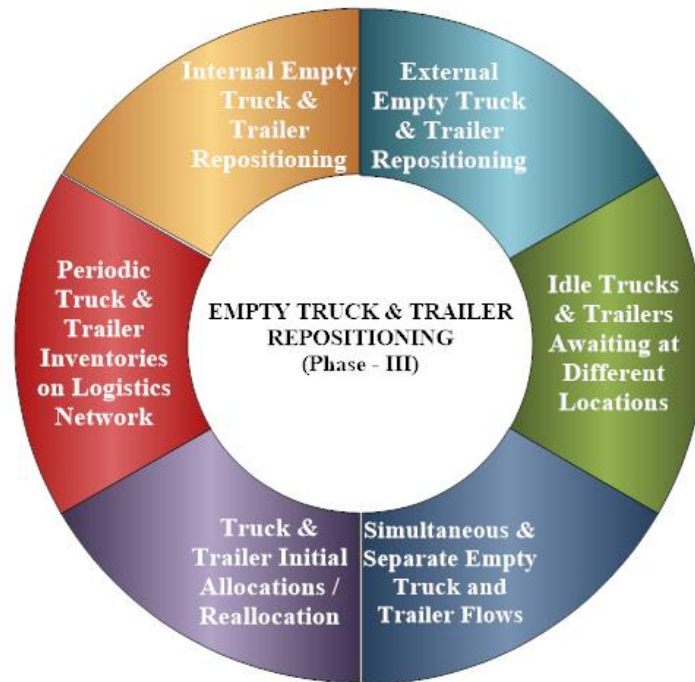


Figure 6.18 Characteristic of phase-III: Periodic truck/trailer inventories and empty truck/trailer flows

The third phase also incorporates the relationships between truck/trailer inventories and relevant fleet sizing/allocation decisions. The inputs and outputs of the third phase can be presented as follows:

Inputs of Phase-III: Periodic truck/trailer inventories on the intermodal logistics network and fleet expansion/reduction decisions:

- All of the inputs of the first and second model development phases,
- Multi-mode load planning results (loaded truck/trailer positions),
- Truck/trailer fleet sizing and allocation decisions,
- Internal and external empty truck/trailer repositions,
- Initial truck and trailer inventory levels at different locations on the intermodal logistics network,
- Inventory holding costs for idle trucks/trailers awaiting at different locations,
- Purchasing price of new trucks with European/Turkish plate and new trailers,
- Sales price of second-hand trucks with European/Turkish plate and old trailers.

Outputs of Phase-III: Periodic truck/trailer inventories on the intermodal logistics network and fleet expansion/reduction decisions:

- Periodic European/Turkish plated truck inventories at the end of each month,
- Periodic trailer inventories at seaports in Turkey and order countries in Europe,
- Relationships between truck/trailer inventories, their fleet size and allocation,
- The amounts purchased European plated new trucks at Germany and Turkish plated trucks and trailers at Turkey in each month,
- The amounts of sold European plated second-hand trucks in Germany and Turkish plated old trucks and trailers in Turkey at each month,
- The amounts of idle or inactive trucks/trailers awaiting at different locations on the intermodal logistics network in each month.

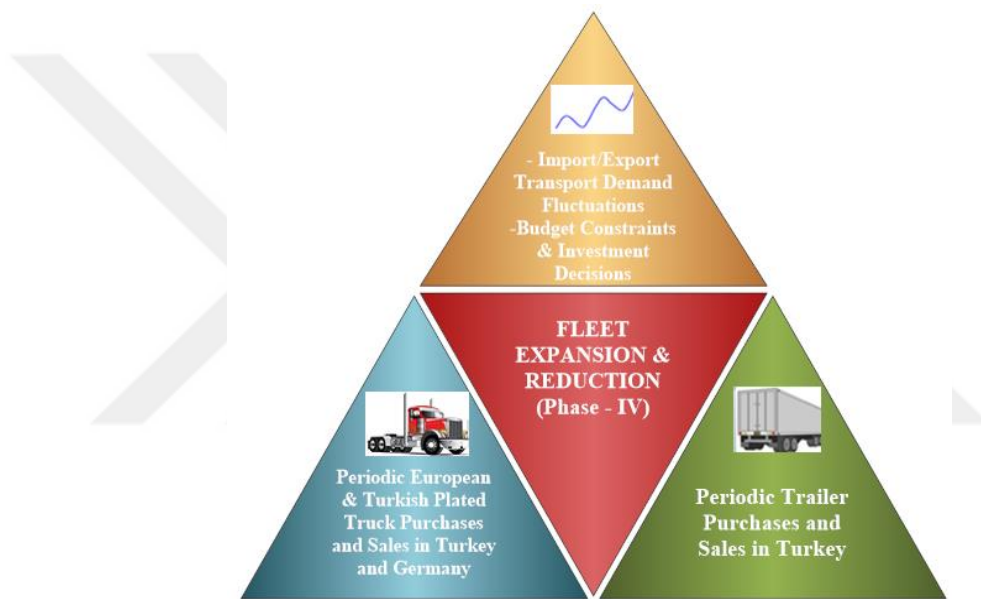


Figure 6.19 Characteristics of Phase-IV: External empty truck/trailer repositions, fleet expansion and reduction decisions

The empty vehicle repositioning concept can be divided into two categories namely internal and external empty truck/trailer repositions as depicted in Figure 6.20 (Baykasoğlu et al., 2015). In fact, these internal and external empty flows may differentiate from the each other in terms of source of the repositioning, physical routes and repositioning times. Due to imbalance of import/export loaded truck positions within the same time period, a need for internal empty truck/trailer repositioning occurs. An appropriate fleet size and allocation can provide minimal internal empty truck/trailer repositions. The internal empty truck/trailer repositions can be performed between a pair of nodes when the loaded truck positions are available among these

nodes. Furthermore, it is assumed throughout this chapter that repositioning times are too short for the internal type empty truck/trailer flows. Thus, the internal empty truck/trailer repositions can be realized within a monthly time period. On the other hand, due to imbalance between the export truck/trailer fleet size and truck/trailer inventories in the consecutive time periods, a need for external empty truck/trailer repositioning arises. In detail, the difference between the outgoing truck fleet size from a node and the truck inventory of this node at the beginning of a time period can be satisfied by the external empty truck repositions. Opposite to the internal empty truck/trailer repositioning, external empty truck/trailer repositions can be performed between the any given two nodes where loaded truck/trailer movements are not possible. Furthermore, it is supposed that external empty truck/trailer repositions cannot be realized within a month. Therefore, repositioning times are equal to one time period for the external type empty truck/trailer flows. In other words, the external empty truck/trailer repositions realized at a time period t will satisfy the truck/trailer requirements of any given node in the subsequent time period, $t + 1$. As shown by the Figure 6.20, cabotage limitations should be considered while performing the external empty truck repositions with different types of plates (European or Turkish).

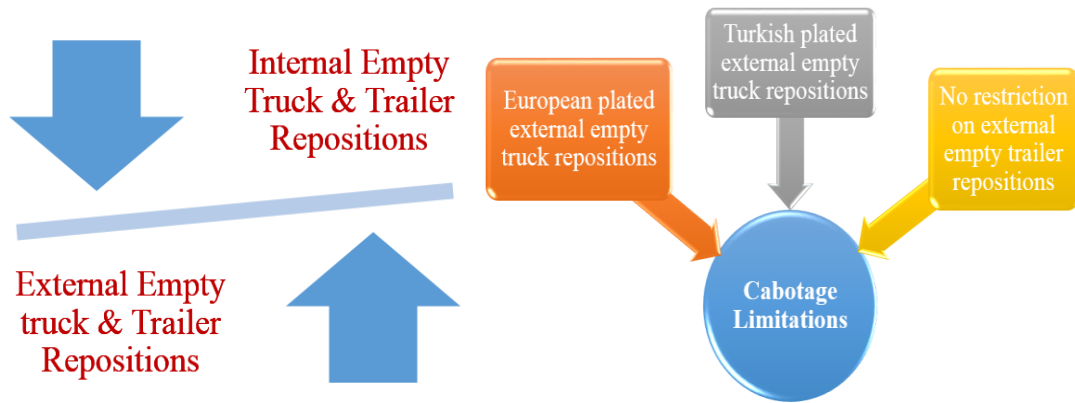


Figure 6.20 The internal and external empty truck/trailer repositions and cabotage limitations

The relationship between the external empty truck and trailer repositions is also taken into account by the fourth model development phase. The inputs and outputs of the fourth phase can be explained as follows:

Inputs of Phase-IV: External empty truck and trailer repositioning issues:

- All of the inputs of the first, second and third model development phases,
- Initial and periodic truck/trailer inventory levels on the logistics network at the end of each month,
- Truck and trailer fleet size optimization results,
- Repositioning cost for empty trucks per kilometer,
- Repositioning cost for trucks with empty trailers per kilometer.

Outputs of Phase-IV: External empty truck and trailer repositioning issues:

- European plated external empty truck repositions and Turkish plated external empty truck repositions by considering cabotage limitations,
- External empty trailer repositions among the order countries themselves by European plated trucks, among the seaports themselves in Turkey by Turkish plated trucks and between seaports in Turkey and order countries by both European or Turkish plated trucks,
- The relationships between the empty truck and trailer repositions.

As it was mentioned in the previous Chapter 5, there are three different transport services in the examined intermodal fleet planning problem. The configuration of intermodal transportation system can be portrayed for these services as in Figure 6.21.

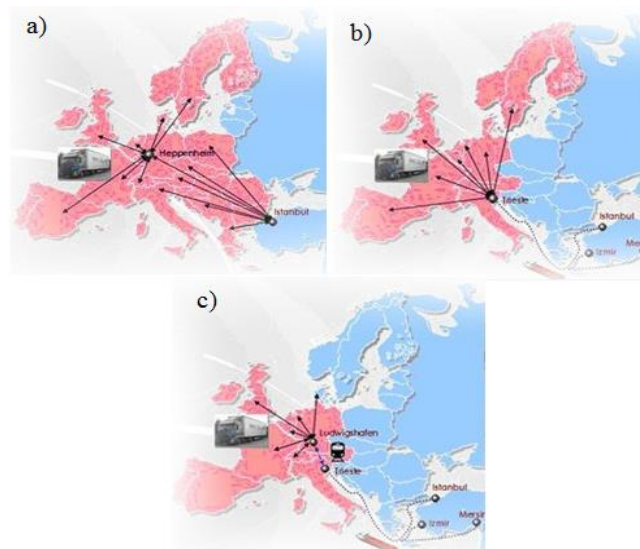


Figure 6.21 Different transportation services: a) Direct road freight transport, b) Combined marine and road transport, c) Intermodal transportation (EKOL, 2016)

Based on the given fixed logistics configuration, the loaded truck/trailer positions and empty truck/trailer repositions between the different locations on the intermodal transportation network can be demonstrated by the following Figures 6.22 - 6.27. According to Figure 6.22, loaded truck positions and internal empty truck repositions can be performed between the seaports in Europe and order countries. In addition, external empty truck repositions can be realized among the seaports themselves in Europe and between the order countries, railway stations and seaports in Europe.

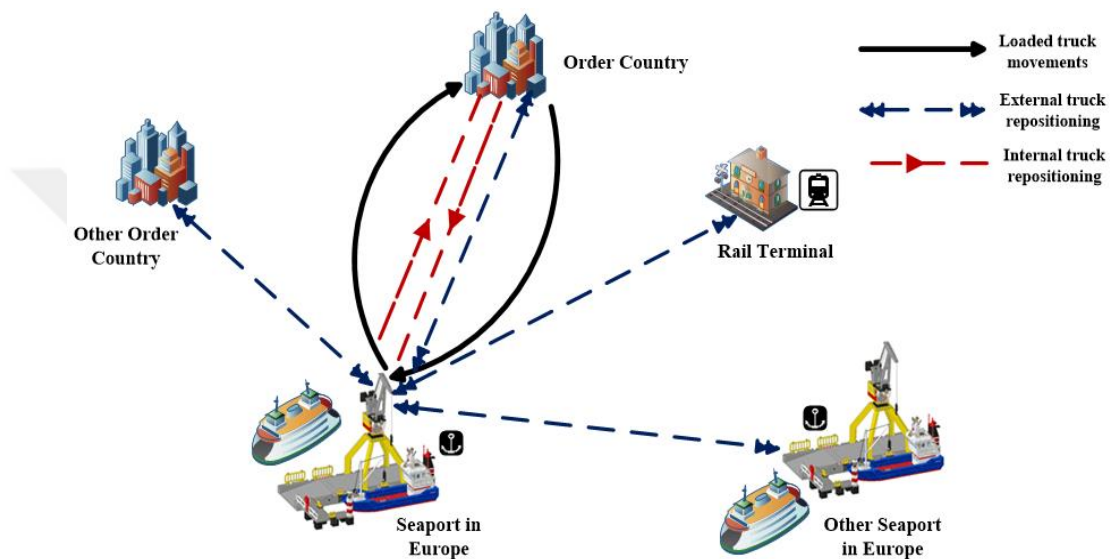


Figure 6.22 Loaded truck positions and empty truck repositions from/to seaports in Europe

Moreover, there are also loaded truck positions and internal empty truck repositions between the railway stations in Europe and order countries as shown in Figure 6.23.

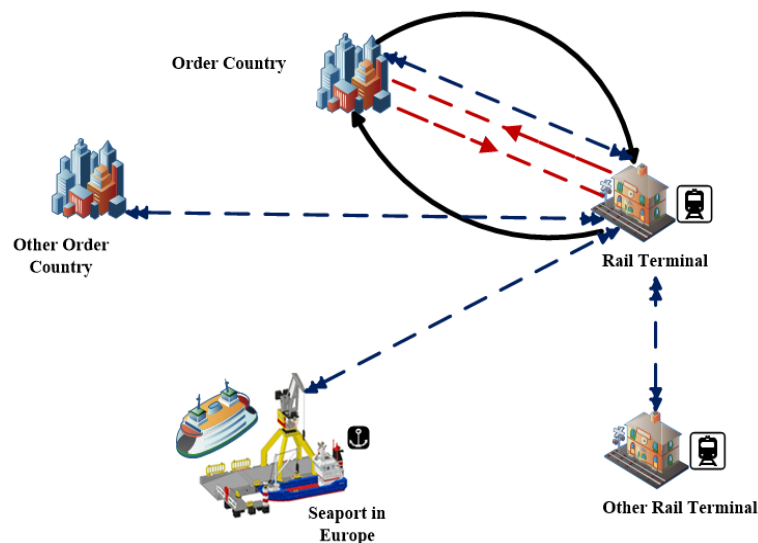


Figure 6.23 Loaded truck positions and empty truck repositions from/to railway stations in Europe

Additionally, external empty trucks can be transferred from the other railway stations, seaports in Europe and order countries in order to meet the truck requirement of a railway terminal. Furthermore, loaded and empty truck flows from/to a seaport in Turkey can be visualized as in the following Figure 6.24. The loaded and internal empty flows can be performed by both European and Turkish plated trucks between the seaports in Turkey and order countries. External Turkish plated empty trucks can also be repositioned among the seaports themselves in Turkey. Moreover, European and Turkish plated trucks can be externally redistributed from the order countries to seaports in Turkey. Turkish plated trucks are also externally repositioned with their empty trailers among the order countries.

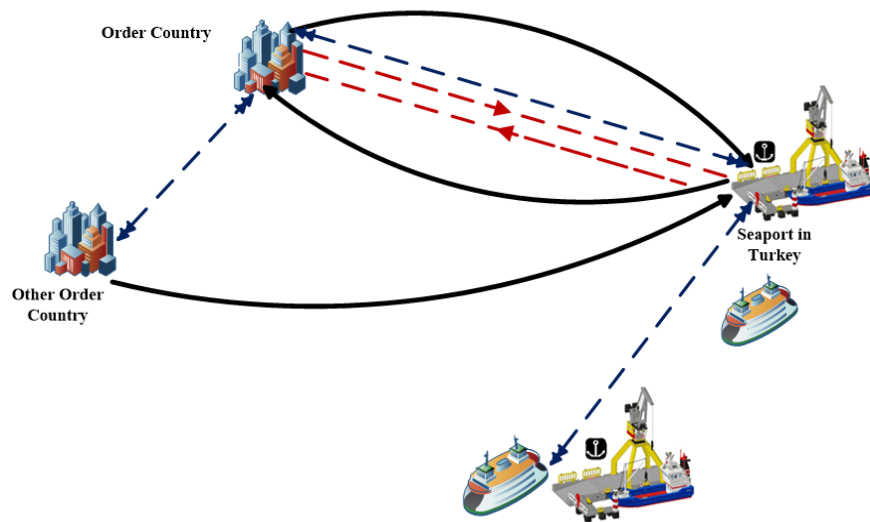


Figure 6.24 Loaded truck positions and empty truck repositions from/to seaports in Turkey

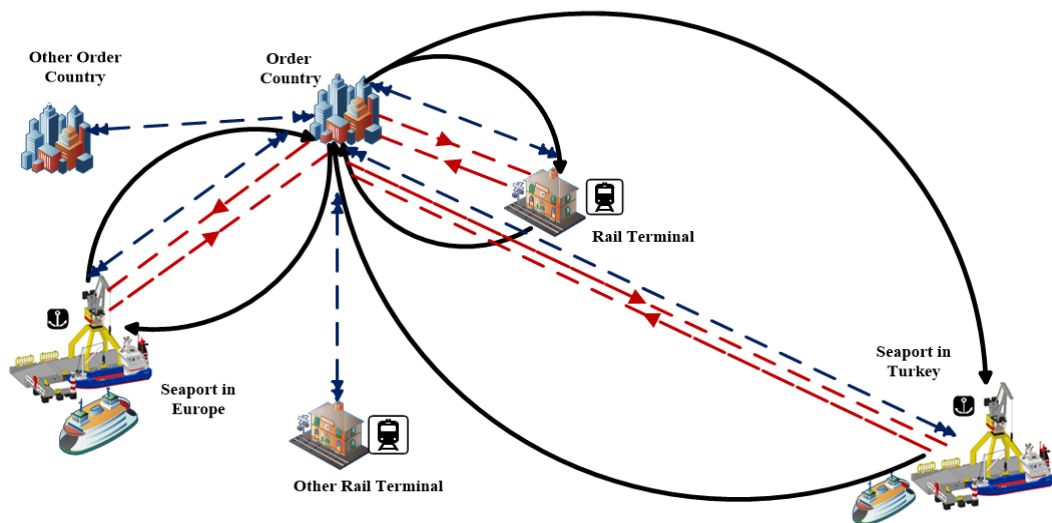


Figure 6.25 Loaded truck positions and empty truck repositions from/to order countries in Europe

Figure 6.25 presents the loaded and empty truck flows from/to the order countries in Europe. Actually, all of the former positions/repositions are aggregated by this network representation. In detail, the loaded truck positions and internal empty truck repositions are realized between the order countries and railway station, seaports in Europe and Turkey. Besides, European plated empty trucks can be externally repositioned among the order countries. The entire loaded and empty flows by European and Turkish plated trucks are summarized as in the following Figure 6.26. It is obviously seen from the following figure that both of the loaded and empty flows of Turkish plated trucks are very limited when compared to European plated trucks.

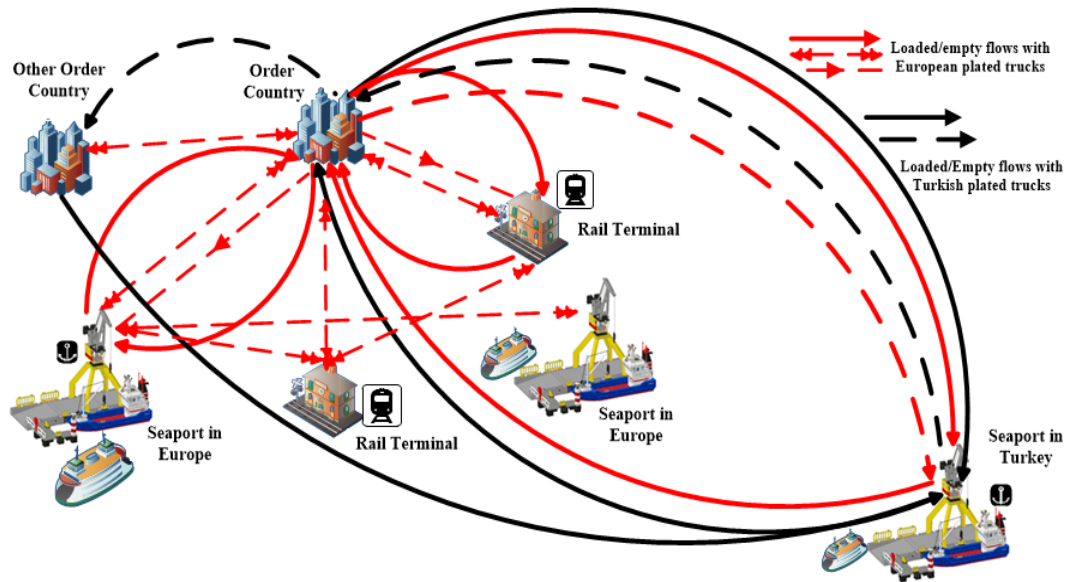


Figure 6.26 Loaded positions and empty repositions by European and Turkish plated trucks on the intermodal logistics network

Finally, the loaded trailer positions and empty trailer repositions between the seaports in Turkey and order countries in Europe are depicted in Figure 6.27. Although the loaded trailers can be shipped by road, marine and rail transports, empty flows of the trailer can be realized by only road transportation. The empty trailers can also be externally repositioned among the order countries, seaports themselves and between the seaports in Turkey and order countries.

Since real-life intermodal fleet planning problems may include different types of uncertainties, i.e., randomness and fuzziness simultaneously, the joint usage of stochastic and fuzzy mathematical programming techniques is required.

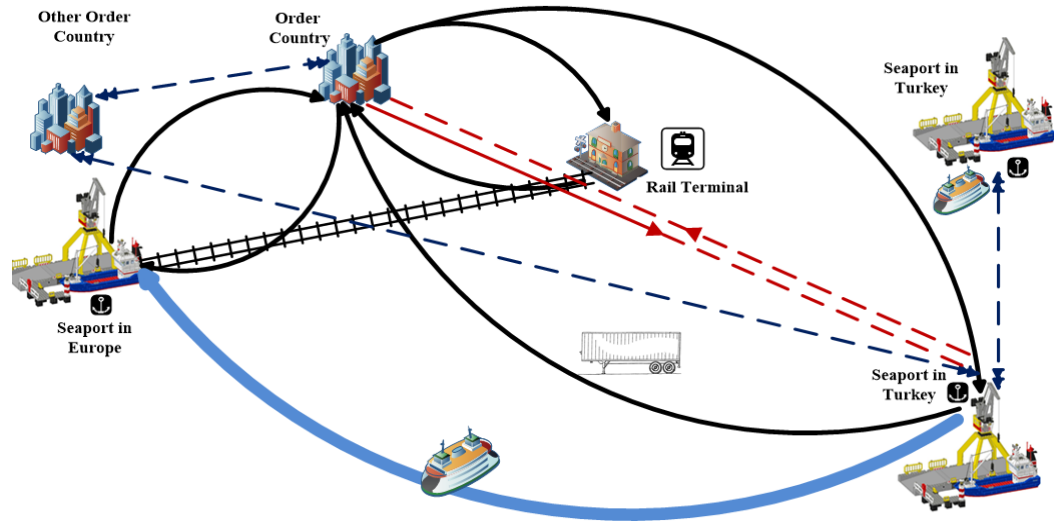


Figure 6.27 Loaded positions and empty repositions of trailers between seaports in Turkey and order countries in Europe

For this reason, after developing the deterministic MIP model of the holistic intermodal fleet planning problem with multiple objectives, a hybrid fuzzy & stochastic programming approach is employed based on chance-constrained stochastic programming and resolution method of Jimenez et al. (2007). The uncertainty modeling phases in intermodal transportation are given by the following Figure 6.28.

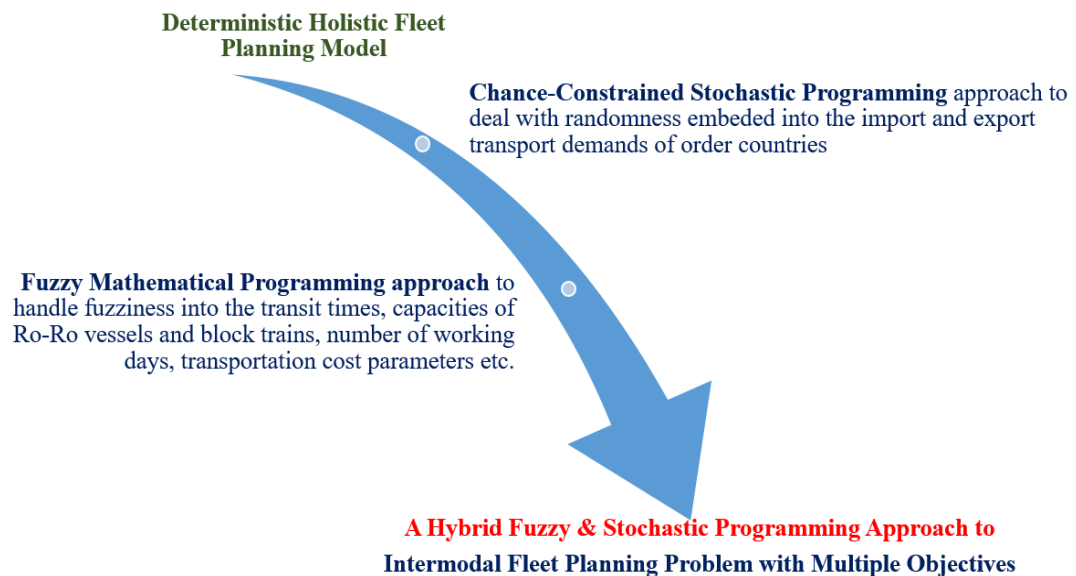


Figure 6.28 Fuzzy & Stochastic model development phases under different types of uncertainties

In addition to the modelling assumptions related to multi-mode load planning phase which is previously formulated in Chapter 5, present intermodal fleet planning model is developed under uncertainty depending on the following additional assumptions.

- It is supposed that monthly import/export freight demands of the order countries are not exactly known and considered as stochastic parameters since they have randomness in nature.
- Since epistemic uncertainty resulting from unavailability or incompleteness of the historical data, insufficient data etc., all of the cost parameters, road-marine-rail transit times, CO₂ emission values of different transportation modes, load capacities of Ro-Ro vessels, maximum number of Ro-Ro trips, lower and upper bounds on Ro-Ro utilizations and block train services are stated as fuzzy parameters and described by possibility distributions.
- Outsourcing is just available for transportation operations between Turkey and order countries. In other words, it is not possible to outsource any truck or trailer for the transportation activities within Europe. For instance, loads cannot be shipped from any seaport in Europe to an order country by outsourcing.
- The working days at order countries in Europe may differ from one period to another. The trucks and trailers are not available 100% percent of a time period.
- In contrast to the heterogeneous truck fleet which consists of European and Turkish plated trucks, the fleet of trailer is supposed to be homogeneous.
- The truck requirements may occur at all nodes on intermodal logistics network such as railway stations, order countries, hubs and seaports in both Turkey and Europe whereas the trailer requirements can only occur at the origin and destination points, i.e., seaports in Turkey and order countries in Europe.
- The empty truck and trailer repositions can only be performed by using road freight transportation. In other words, empty trailers cannot be repositioned by means of Ro-Ro vessels and block trains.
- It is possible to reposition just empty trucks without any trailer between the seaports, rail terminals and order countries. In detail, empty trucks can be transferred solely from the seaports to rail terminals or order countries in order to support the transportation operations at these nodes and thus increase the service level by decreasing the waiting times.
- It is not possible to reposition the Turkish plated empty trucks without trailers in Europe itself due to the cabotage limitations and vice versa. This means that European plated empty trucks also cannot be repositioned in Turkey. On the

other hand, Turkish plated trucks can be repositioned among the order countries in Europe on condition that moving with their own empty trailers to load extra freights and return to Turkey. On the other hand, there is no positional limitation on empty trailer repositioning in both Turkey and Europe.

- The empty trailers can be repositioned by both European and Turkish plated trucks internally or externally between Turkey and order countries in Europe.
- The European plated empty trucks can be repositioned from any order country to a seaport or rail station without trailers. Furthermore, these trucks can also be repositioned among the order countries themselves with their empty trailers.
- On the contrary to internal empty truck/trailer repositioning where the empty flows can satisfy the truck/trailer requirements within the same time period, the external empty truck/trailer repositions at a time period can meet the requirements of the next period.
- While determining the truck and trailer fleet sizes, road-marine-rail transit times are considered for only loaded movements. Because, empty truck or trailer repositioning times are already involved by fleet allocation decisions to satisfy the loaded positions within a pre-specified time period. These repositioning times are also taken into account by the second objective function of the proposed mathematical programming model.
- It is assumed that the travel time of a loaded truck between any locations is different from the travel time of an empty truck. For this reason, in addition to the previous transit times which considers only the loaded movements, the empty repositioning times between the locations should also be described.
- Purchases and sales of European plated trucks can only be performed at the different regions of Germany. Conversely, newly purchased or second-hand Turkish plated trucks can join or leave the intermodal transportation system at Istanbul. Similarly, trailer purchases and sales can be realized at Istanbul.

The network notation and mathematical nomenclature with stochastic and fuzzy model parameters are also introduced in Appendices A1, A2 and A3. In this chapter, the first goal of the proposed holistic intermodal fleet planning model is reformulated as in Equations (6.8) – (6.18). In fact, the road freight transportation cost is divided into three categories, i.e., costs for loaded trucks, empty trucks and trucks with empty

trailers. The empty truck and trailer repositioning costs are defined for both internal and external empty flows. Moreover, fixed ownership costs of European/Turkish plated trucks and trailers are taken into account by the first objective function for both active and idle resources. Finally, purchasing costs for new trucks/trailers and revenues obtained from the sales of second hand trucks/trailers are also included so as to determine periodic fleet expansion and reduction.

Goal-1: Minimize overall transport costs throughout intermodal logistics network:

$$\begin{aligned} \text{Min } \bar{Z}1_{\text{Cost}} \cong & \bar{Z}1_{\text{marine}} + \bar{Z}1_{\text{railway}} + \bar{Z}1_{\text{road}} + \bar{Z}1_{\text{outsourcing}} + \bar{Z}1_{\text{ownership}} + \\ & \bar{Z}1_{\text{internal-reposition}} + \bar{Z}1_{\text{external-reposition}} + \bar{Z}1_{\text{idle}} + \bar{Z}1_{\text{purchasing}} - \bar{Z}1_{\text{sales}} \end{aligned} \quad (6.8)$$

(I) Maritime transportation costs by the company-owned Ro-Ro vessels and other logistics service providers' Ro-Ro vessels:

$$\begin{aligned} \bar{Z}1_{\text{marine}} \cong & \sum_{(i,j) \notin L_{ij}} \sum_{t \in T} R_{ijt}^{\text{exp}} \cdot \bar{C}o_{ij}^{\text{exp}} + \sum_{(j,i) \notin L_{ji}} \sum_{t \in T} R_{jit}^{\text{imp}} \cdot \bar{C}o_{ji}^{\text{imp}} + \\ & \sum_{(i,j) \notin C_{ij}} \sum_{t \in T} P_{ijt}^{\text{exp}} \cdot \bar{C}p_{ij}^{\text{exp}} + \sum_{(j,i) \notin C_{ji}} \sum_{t \in T} P_{jit}^{\text{imp}} \cdot \bar{C}p_{ji}^{\text{imp}} \end{aligned} \quad (6.9)$$

(II) Railway transportation costs by fixed schedule of block trains and flexible schedule of public trains:

$$\begin{aligned} \bar{Z}1_{\text{railway}} \cong & \sum_{(j,k) \notin L_{jk}} \sum_{t \in T} S_{jkt}^{\text{exp}} \cdot \bar{C}b_{jk}^{\text{exp}} + \sum_{(k,j) \notin L_{kj}} \sum_{t \in T} S_{kjt}^{\text{imp}} \cdot \bar{C}b_{kj}^{\text{imp}} + \sum_{(j,k) \notin C_{jk}} \sum_{t \in T} P_{jkt}^{\text{exp}} \cdot \bar{C}p_{jk}^{\text{exp}} + \\ & \sum_{(k,j) \notin C_{kj}} \sum_{t \in T} P_{kjt}^{\text{imp}} \cdot \bar{C}p_{kj}^{\text{imp}} + \sum_{k' \in T_k} \sum_{k^* \in G_k} \sum_{t \in T} P_{k'k^*t}^{\text{imp}} \cdot \bar{C}p_{k^*k'}^{\text{imp}} + \sum_{k' \in T_k} \sum_{k^* \in G_k} \sum_{t \in T} P_{k'k^*t}^{\text{exp}} \cdot \bar{C}p_{k^*k'}^{\text{exp}} \end{aligned} \quad (6.10)$$

(III) Road transport cost by European/Turkish plated trucks for loaded movements:

$$\begin{aligned} \bar{Z}1_{\text{road}} \cong & \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{jlt}^{\text{exp}} \cdot d_{jl}^r \cdot \bar{C}r + \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{ljt}^{\text{imp}} \cdot d_{lj}^r \cdot \bar{C}r + \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{klt}^{\text{exp}} \cdot d_{kl}^r \cdot \bar{C}r + \\ & \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{lkt}^{\text{imp}} \cdot d_{lk}^r \cdot \bar{C}r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (V_{ilt}^{\text{exp}} + VT_{ilt}^{\text{exp}}) \cdot d_{il}^r \cdot \bar{C}r + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (V_{lit}^{\text{imp}} + VT_{lit}^{\text{imp}}) \cdot d_{li}^r \cdot \bar{C}r \end{aligned} \quad (6.11)$$

(IV) Outsourcing costs in direct road and combined marine & road transportation:

$$\bar{Z}1_{outsourcing} \cong \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{ilt}^{exp} \cdot \bar{S}C_{ilt}^{exp} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{lit}^{imp} \cdot \bar{S}C_{lit}^{imp} \quad (6.12)$$

(V) Fixed ownership costs for European/Turkish plated trucks and trailers:

$$\begin{aligned} \bar{Z}1_{ownership} \cong & \bar{O}WC_{Euro}^{Truck} \cdot \left(\sum_{j \in J} \sum_{l \in L} \sum_{t \in T} (VS_{jlt}^{exp} + VS_{ljt}^{imp}) + \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} (VS_{klt}^{exp} + VS_{lkt}^{imp}) \right) \\ & + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (EP_{ilt}^{exp} + EP_{lit}^{imp}) + \bar{O}WC_{Turk}^{Truck} \cdot \left(\sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (TP_{ilt}^{exp} + TP_{lit}^{imp}) \right) + \\ & \bar{O}WN^{Trail} \cdot \left(\sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (TS_{ilt}^{exp} + TS_{lit}^{imp}) \right) \end{aligned} \quad (6.13)$$

(VI) Internal empty truck and trailer repositioning costs:

$$\begin{aligned} \bar{Z}1_{internal-reposition} \cong & \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{jlt}^{rep} \cdot d_{jl}^r \cdot \bar{R}C^v + \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{ljt}^{rep} \cdot d_{lj}^r \cdot \bar{R}C^v + \\ & \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{klt}^{rep} \cdot d_{kl}^r \cdot \bar{R}C^v + \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{lkt}^{rep} \cdot d_{lk}^r \cdot \bar{R}C^v + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VE_{ilt}^{rep} + VT_{ilt}^{rep}) \cdot d_{il}^r \cdot \bar{R}C^v + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VE_{lit}^{rep} + VT_{lit}^{rep}) \cdot d_{li}^r \cdot \bar{R}C^v + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} TR_{ilt}^{rep} \cdot d_{il}^r \cdot \bar{R}C^{Tr} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} TR_{lit}^{rep} \cdot d_{li}^r \cdot \bar{R}C^{Tr} \end{aligned} \quad (6.14)$$

(VII) External empty truck and trailer repositioning costs:

$$\begin{aligned} \bar{Z}1_{external-reposition} \cong & \sum_{k \in K} \sum_{j \in J} \sum_{t \in T} VR_{jkt}^{rep} \cdot d_{jk}^r \cdot \bar{R}C^v + \sum_{k \in K} \sum_{j \in J} \sum_{t \in T} VR_{kjt}^{rep} \cdot d_{kj}^r \cdot \bar{R}C^v + \\ & \sum_{j \in J} \sum_{j' \in J \setminus \{j\}} \sum_{t \in T} VR_{j'jt}^{rep} \cdot d_{j'j}^r \cdot \bar{R}C^v + \sum_{l \in L} \sum_{j \in J} \sum_{t \in T} VR_{jlt}^{rep} \cdot d_{jl}^r \cdot \bar{R}C^v + \sum_{l \in L} \sum_{j \in J} \sum_{t \in T} VR_{ljt}^{rep} \cdot d_{lj}^r \cdot \bar{R}C^v \\ & \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} VR_{l'tl}^{rep} \cdot d_{l'l}^r \cdot \bar{R}C^v + \sum_{i \in I} \sum_{l' \in I \setminus \{i\}} \sum_{t \in T} VR_{l'it}^{rep} \cdot d_{l'i}^r \cdot \bar{R}C^v + \sum_{l \in L} \sum_{k \in K} \sum_{t \in T} VR_{klt}^{rep} \cdot d_{kl}^r \cdot \bar{R}C^v + \\ & \sum_{l \in L} \sum_{k \in K} \sum_{t \in T} VR_{lkt}^{rep} \cdot d_{lk}^r \cdot \bar{R}C^v + \sum_{k \in K} \sum_{k' \in K \setminus \{k\}} \sum_{t \in T} VR_{k'kt}^{rep} \cdot d_{k'k}^r \cdot \bar{R}C^v + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VRE_{ilt}^{rep} + VRT_{ilt}^{rep}) \cdot d_{il}^r \cdot \bar{R}C^v + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VRE_{lit}^{rep} + VRT_{lit}^{rep}) \cdot d_{li}^r \cdot \bar{R}C^v + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} XTR_{ilt}^{rep} \cdot d_{il}^r \cdot \bar{R}C^{Tr} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} XTR_{lit}^{rep} \cdot d_{li}^r \cdot \bar{R}C^{Tr} + \sum_{i \in I} \sum_{l' \in I \setminus \{i\}} \sum_{t \in T} TR_{l'it}^{rep} \cdot d_{l'i}^r \cdot \bar{R}C^{Tr} + \\ & \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} TR_{l'tl}^{rep} \cdot d_{l'l}^r \cdot \bar{R}C^{Tr} + \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} TTR_{l'it}^{rep} \cdot d_{l'l}^r \cdot \bar{R}C^{Tr} \end{aligned} \quad (6.15)$$

(VIII) Fixed ownership costs for idle or inactive trucks and trailers:

$$\begin{aligned} \widetilde{Z1}_{idle} \cong \widetilde{OWC}_{Euro}^{Truck} \cdot \left(\sum_{j \in J} \sum_{t \in T} IVJ_{jt} + \sum_{k \in K} \sum_{t \in T} IVK_{kt} + \sum_{l \in L} \sum_{t \in T} IVL_{lt}^E + \sum_{i \in I} \sum_{t \in T} IVI_{it}^E \right) + \\ \widetilde{OWC}_{Turk}^{Truck} \cdot \left(\sum_{l \in L} \sum_{t \in T} IVL_{lt}^T + \sum_{i \in I} \sum_{t \in T} IVI_{it}^T \right) + \widetilde{OWN}^{Trail} \cdot \left(\sum_{l \in L} \sum_{t \in T} ITL_{lt} + \sum_{i \in I} \sum_{t \in T} ITI_{it} \right) \end{aligned} \quad (6.16)$$

(IX) Purchasing costs for European/Turkish plated new trucks and trailers:

$$\widetilde{Z1}_{purchasing} \cong \sum_{i \in PR_I} \sum_{t \in T} Pr_{it}^T \cdot \widetilde{PCV}^T + \sum_{l \in PR_L} \sum_{t \in T} Pr_{lt}^E \cdot \widetilde{PCV}^E + \sum_{i \in PR_I} \sum_{t \in T} Prt_{it} \cdot \widetilde{PCT} \quad (6.17)$$

(X) Total revenue obtained from the sales of second-hand trucks and trailers:

$$\widetilde{Z1}_{sales} \cong \sum_{i \in PR_I} \sum_{t \in T} Sp_{it}^T \cdot \widetilde{SV}^T + \sum_{l \in PR_L} \sum_{t \in T} Sp_{lt}^E \cdot \widetilde{SV}^E + \sum_{i \in PR_I} \sum_{t \in T} Spt_{it} \cdot \widetilde{ST} \quad (6.18)$$

The second goal of the proposed model can also be revised as in the following Equations from (6.19) to (6.25) by the inclusion of internal and external empty truck and trailer repositioning times.

Goal-2: Minimize the total transit time including loading/unloading times, travel times and awaiting times at the terminals:

$$\begin{aligned} \text{Min } \widetilde{Z2}_{Transit-time} \cong \widetilde{Z2}_{direct-road} + \widetilde{Z2}_{combined-marine} + \widetilde{Z2}_{intermodal} + \widetilde{Z2}_{outsourcing} \\ + \widetilde{Z2}_{internal-reposition} + \widetilde{Z2}_{external-reposition} \end{aligned} \quad (6.19)$$

(I) Road freight transit times for loaded truck movements:

$$\widetilde{Z2}_{direct-road} \cong \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{ilt}^{exp} \cdot \widetilde{T}_{il}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{lit}^{imp} \cdot \widetilde{T}_{li}^r \quad (6.20)$$

(II) Combined marine and road freight transit times:

$$\widetilde{Z2}_{combined-marine} \cong \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ijlt}^{exp} \cdot (\widetilde{T}_{ij}^m + \widetilde{T}_{jl}^r) + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ljit}^{imp} \cdot (\widetilde{T}_{lj}^r + \widetilde{T}_{ji}^m) \quad (6.21)$$

(III) Combined marine, rail and road transit times in intermodal transportation:

$$\begin{aligned}
\widetilde{Z}_{intermodal} \cong & \sum_{i \in I} \sum_{j \in J} \sum_{k \notin G_k} \sum_{l \in L} \sum_{t \in T} Z_{ijkl}^{exp} \cdot (\tilde{T}_{ij}^m + \tilde{T}_{jk}^t + \tilde{T}_{kl}^r) + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k \notin G_k} \sum_{l \in L} \sum_{t \in T} Z_{lkjit}^{imp} \cdot (\tilde{T}_{lk}^r + \tilde{T}_{kj}^t + \tilde{T}_{ji}^m) + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k' \in T_k} \sum_{k^* \in G_k} \sum_{l \in G_l} \sum_{t \in T} Z_{ijk^*lt}^{exp} \cdot (\tilde{T}_{ij}^m + \tilde{T}_{jk'}^t + \tilde{T}_{k'^*k^*}^t + \tilde{T}_{k^*l}^r) + \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{k' \in T_k} \sum_{l \in G_l} \sum_{t \in T} Z_{lk^*jit}^{imp} \cdot (\tilde{T}_{lk^*}^r + \tilde{T}_{k^*k'}^t + \tilde{T}_{k'l}^t + \tilde{T}_{ji}^m)
\end{aligned} \tag{6.22}$$

(IV) Marine and road freight transit times for outsourced transportation services:

$$\begin{aligned}
\widetilde{Z}_{outsourcing} \cong & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{ilt}^{exp} \cdot \left[\tilde{\varphi}^{out} \cdot \tilde{T}_{il}^r + (1 - \tilde{\varphi}^{out}) \cdot \sum_{j \in J} \tilde{T}_{ij}^m + \tilde{T}_{jl}^r \right] + \\
& \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{lit}^{imp} \cdot \left[\tilde{\varphi}^{out} \cdot \tilde{T}_{li}^r + (1 - \tilde{\varphi}^{out}) \cdot \sum_{j \in J} \tilde{T}_{lj}^r + \tilde{T}_{ji}^m \right]
\end{aligned} \tag{6.23}$$

(V) Road freight transit times for internal empty truck and trailer movements:

$$\begin{aligned}
\widetilde{Z}_{internal-reposition} \cong & \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{jlt}^{rep} \cdot \tilde{T}_{jl}^r + \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{ljt}^{rep} \cdot \tilde{T}_{lj}^r + \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{klt}^{rep} \cdot \tilde{T}_{kl}^r + \\
& \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{lkt}^{rep} \cdot \tilde{T}_{lk}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VE_{ilt}^{rep} + VT_{ilt}^{rep}) \cdot \tilde{T}_{il}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} TR_{ilt}^{rep} \cdot \tilde{T}_{il}^r + \\
& \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VE_{lit}^{rep} + VT_{lit}^{rep}) \cdot \tilde{T}_{li}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} TR_{lit}^{rep} \cdot \tilde{T}_{li}^r
\end{aligned} \tag{6.24}$$

(VI) Road freight transit times for the external empty truck and trailer movements:

$$\begin{aligned}
\widetilde{Z}_{external-rep} \cong & \sum_{k \in K} \sum_{j \in J} \sum_{t \in T} VR_{jkt}^{rep} \cdot \tilde{T}_{jk}^r + \sum_{k \in K} \sum_{j \in J} \sum_{t \in T} VR_{kjt}^{rep} \cdot \tilde{T}_{kj}^r + \sum_{j \in J} \sum_{j' \in J \setminus \{j\}} \sum_{t \in T} VR_{j'jt}^{rep} \cdot \tilde{T}_{j'j}^r \\
& + \sum_{l \in L} \sum_{j \in J} \sum_{t \in T} VR_{jlt}^{rep} \cdot \tilde{T}_{jl}^r + \sum_{l \in L} \sum_{j \in J} \sum_{t \in T} VR_{ljt}^{rep} \cdot \tilde{T}_{lj}^r + \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} VR_{l'tl}^{rep} \cdot \tilde{T}_{l'l}^r + \\
& \sum_{i \in I} \sum_{i' \in I \setminus \{i\}} \sum_{t \in T} VR_{i'it}^{rep} \cdot \tilde{T}_{i'i}^r + \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} VR_{klt}^{rep} \cdot \tilde{T}_{kl}^r + \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} VR_{lkt}^{rep} \cdot \tilde{T}_{lk}^r + \\
& \sum_{k \in K} \sum_{k' \in K \setminus \{k\}} \sum_{t \in T} VR_{k'kt}^{rep} \cdot \tilde{T}_{k'k}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VRE_{ilt}^{rep} + VRT_{ilt}^{rep}) \cdot \tilde{T}_{il}^r + \\
& \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VRE_{lit}^{rep} + VRT_{lit}^{rep}) \cdot \tilde{T}_{li}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} XTR_{ilt}^{rep} \cdot d_{il} \cdot \tilde{T}_{il}^r + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} XTR_{lit}^{rep} \cdot \tilde{T}_{li}^r + \\
& \sum_{i \in I} \sum_{i' \in I \setminus \{i\}} \sum_{t \in T} TR_{i'it}^{rep} \cdot \tilde{T}_{i'i}^r + \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} TR_{l'lt}^{rep} \cdot \tilde{T}_{l'l}^r + \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} TTR_{l'lt}^{rep} \cdot \tilde{T}_{l'l}^r
\end{aligned} \tag{6.25}$$

The last goal which provides environmenally conscious fleet plans is also extended as follows by adding CO₂ emission values during empty truck/trailer repositions.

Goal-3: Minimize the total environmental impact or total CO₂ emissions by different transportation modes:

$$\begin{aligned} \text{Min } \tilde{Z}_{CO_2\text{-emission}} \cong & \tilde{Z}_{road} + \tilde{Z}_{marine} + \tilde{Z}_{railway} + \tilde{Z}_{outsourcing} + \\ & \tilde{Z}_{internal\text{-reposition}} + \tilde{Z}_{external\text{-reposition}} \end{aligned} \quad (6.26)$$

(I) Total CO₂ emissions from the loaded truck movements by road freight transport:

$$\begin{aligned} \tilde{Z}_{road} \cong & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{ilt}^{exp} \cdot d_{il}^r \cdot \overline{CO_2^R} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} X_{ilt}^{imp} \cdot d_{li}^r \cdot \overline{CO_2^R} + \\ & + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{jit}^{imp} \cdot d_{lj}^r \cdot \overline{CO_2^R} + \sum_{i \in I} \sum_{j \in J} \sum_{k \notin G_k} \sum_{l \in L} \sum_{t \in T} Z_{ijklt}^{exp} \cdot d_{kl}^r \cdot \overline{CO_2^R} + \\ & \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{l \in L} \sum_{t \in T} Z_{ijk^*lt}^{exp} \cdot d_{k^*l}^r \cdot \overline{CO_2^R} + \sum_{i \in I} \sum_{j \in J} \sum_{k \notin G_k} \sum_{l \in L} \sum_{t \in T} Z_{lkjlt}^{imp} \cdot d_{lk}^r \cdot \overline{CO_2^R} + \\ & \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} Y_{ijlt}^{exp} \cdot d_{jl}^r \cdot \overline{CO_2^R} + \sum_{i \in I} \sum_{j \in J} \sum_{k^* \in G_k} \sum_{l \in L} \sum_{t \in T} Z_{lk^*jit}^{imp} \cdot d_{lk^*}^r \cdot \overline{CO_2^R} \end{aligned} \quad (6.27)$$

(II) Total CO₂ emissions from the maritime logistics services:

$$\begin{aligned} \tilde{Z}_{marine} \cong & \sum_{(i,j) \notin L_{ij}} \sum_{t \in T} R_{ijt}^{exp} \cdot d_{ij}^m \cdot \overline{CO_2^M} + \sum_{(j,i) \notin L_{ji}} \sum_{t \in T} R_{jit}^{imp} \cdot d_{ji}^m \cdot \overline{CO_2^M} + \\ & \sum_{(i,j) \notin C_{ij}} \sum_{t \in T} P_{ijt}^{exp} \cdot d_{ij}^m \cdot \overline{CO_2^M} + \sum_{(j,i) \notin C_{ji}} \sum_{t \in T} P_{jit}^{imp} \cdot d_{ji}^m \cdot \overline{CO_2^M} \end{aligned} \quad (6.28)$$

(III) Total CO₂ emissions from the railway transport services:

$$\begin{aligned} \tilde{Z}_{railway} \cong & \sum_{(j,k) \notin L_{jk}} \sum_{t \in T} S_{jkt}^{exp} \cdot \widetilde{Cap}_{jk}^{exp} \cdot d_{jk}^t \cdot \overline{CO_2^T} + \sum_{(k,j) \notin L_{kj}} \sum_{t \in T} S_{kjt}^{imp} \cdot \widetilde{Cap}_{kj}^{imp} \cdot d_{kj}^t \cdot \overline{CO_2^T} + \\ & \sum_{(k,j) \notin C_{kj}} \sum_{t \in T} P_{kjt}^{imp} \cdot d_{kj}^t \cdot \overline{CO_2^T} + \sum_{k' \in T_k} \sum_{k^* \in G_k} \sum_{t \in T} P_{k'k^*t}^{exp} \cdot d_{k'k^*}^t \cdot \overline{CO_2^T} + \\ & \sum_{(j,k) \notin C_{jk}} \sum_{t \in T} P_{jkt}^{exp} \cdot d_{jk}^t \cdot \overline{CO_2^T} + \sum_{k' \in T_k} \sum_{k^* \in G_k} \sum_{t \in T} P_{k^*k't}^{imp} \cdot d_{k^*k'}^t \cdot \overline{CO_2^T} \end{aligned} \quad (6.29)$$

(IV) Total CO₂ emissions from the maritime logistics and road freight transport of outsourced services:

$$\begin{aligned} \widetilde{Z3}_{outsourcing} \cong & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{ilt}^{exp} \cdot \left[\tilde{\varphi}^{out} \cdot d_{il}^r \cdot \widetilde{CO2}^R + (1 - \tilde{\varphi}^{out}) \cdot \sum_{j \in J} d_{ij}^m \cdot \widetilde{CO2}^M + d_{jl}^r \cdot \widetilde{CO2}^R \right] \\ & + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} O_{lit}^{imp} \cdot \left[\tilde{\varphi}^{out} \cdot d_{li}^r \cdot \widetilde{CO2}^R + (1 - \tilde{\varphi}^{out}) \cdot \sum_{j \in J} d_{lj}^r \cdot \widetilde{CO2}^R + d_{ji}^m \cdot \widetilde{CO2}^M \right] \end{aligned} \quad (6.30)$$

(V) Total CO₂ emissions from the internal empty truck and trailer movements in road transportation:

$$\begin{aligned} \widetilde{Z3}_{internal-reposition} \cong & \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{ljt}^{rep} \cdot d_{lj}^r \cdot \widetilde{CO2}^{RE} + \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} V_{jlt}^{rep} \cdot d_{jl}^r \cdot \widetilde{CO2}^{RE} + \\ & \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{klt}^{rep} \cdot d_{kl}^r \cdot \widetilde{CO2}^{RE} + \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} V_{lkt}^{rep} \cdot d_{lk}^r \cdot \widetilde{CO2}^{RE} + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VE_{ilt}^{rep} + VT_{ilt}^{rep}) \cdot d_{il}^r \cdot \widetilde{CO2}^{RE} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VE_{lit}^{rep} + VT_{lit}^{rep}) \cdot d_{li}^r \cdot \widetilde{CO2}^{RE} + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} TR_{ilt}^{rep} \cdot d_{il}^r \cdot \widetilde{CO2}^R + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} TR_{lit}^{rep} \cdot d_{li}^r \cdot \widetilde{CO2}^R \end{aligned} \quad (6.31)$$

(VI) Total CO₂ emissions from the external empty truck and trailer movements in road transportation:

$$\begin{aligned} \widetilde{Z3}_{external-reposition} \cong & \sum_{k \in K} \sum_{j \in J} \sum_{t \in T} VR_{jkt}^{rep} \cdot d_{jk}^r \cdot \widetilde{CO2}^{RE} + \sum_{k \in K} \sum_{j \in J} \sum_{t \in T} VR_{kjt}^{rep} \cdot d_{kj}^r \cdot \widetilde{CO2}^{RE} + \\ & \sum_{j \in J} \sum_{j' \in J \setminus \{j\}} \sum_{t \in T} VR_{j'jt}^{rep} \cdot d_{j'j}^r \cdot \widetilde{CO2}^{RE} + \sum_{l \in L} \sum_{j \in J} \sum_{t \in T} VR_{jlt}^{rep} \cdot d_{jl}^r \cdot \widetilde{CO2}^{RE} + \sum_{l \in L} \sum_{j \in J} \sum_{t \in T} VR_{ljt}^{rep} \cdot d_{lj}^r \cdot \widetilde{CO2}^{RE} \\ & \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} VR_{l't}^{rep} \cdot d_{l'l}^r \cdot \widetilde{CO2}^{RE} + \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} VR_{l't}^{rep} \cdot d_{l'i}^r \cdot \widetilde{CO2}^{RE} + \\ & \sum_{l \in L} \sum_{k \in K} \sum_{t \in T} VR_{klt}^{rep} \cdot d_{kl}^r \cdot \widetilde{CO2}^{RE} + \sum_{l \in L} \sum_{k \in K} \sum_{t \in T} VR_{lkt}^{rep} \cdot d_{lk}^r \cdot \widetilde{CO2}^{RE} + \\ & \sum_{k \in K} \sum_{k' \in K \setminus \{k\}} \sum_{t \in T} VR_{k'kt}^{rep} \cdot d_{k'k}^r \cdot \widetilde{CO2}^{RE} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VRE_{ilt}^{rep} + VRT_{ilt}^{rep}) \cdot d_{il}^r \cdot \widetilde{CO2}^{RE} + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} (VRE_{lit}^{rep} + VRT_{lit}^{rep}) \cdot d_{li}^r \cdot \widetilde{CO2}^{RE} + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} XTR_{ilt}^{rep} \cdot d_{il}^r \cdot \widetilde{CO2}^R + \\ & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} XTR_{lit}^{rep} \cdot d_{li}^r \cdot \widetilde{CO2}^R + \sum_{i \in I} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} TR_{i'l't}^{rep} \cdot d_{i'l}^r \cdot \widetilde{CO2}^R + \\ & \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} TR_{l'i't}^{rep} \cdot d_{l'i}^r \cdot \widetilde{CO2}^R + \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{t \in T} TTR_{l'i't}^{rep} \cdot d_{l'i}^r \cdot \widetilde{CO2}^R \end{aligned} \quad (6.32)$$

Phase-I: Multi-mode load planning or intermodal freight transportation planning.

The constraints which are related to intermodal freight transportation planning problem can be expressed by the following Equations (6.33) to (6.70):

i. Periodic load allocation to different modes of transport in order to satisfy probabilistic import/export transport demands of order countries:

$$Pr \left\{ X_{ilt}^{exp} + \sum_{j \in J} Y_{ijlt}^{exp} + \sum_{j \in D_j} \sum_{k \in K} Z_{ijklt}^{exp} + O_{ilt}^{exp} \geq De_{ilt}^{exp} \right\} \geq \alpha_{ilt} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.33)$$

$$Pr \left\{ X_{lit}^{imp} + \sum_{j \in J} Y_{ljit}^{imp} + \sum_{j \in D_j} \sum_{k \in K} Z_{lkjit}^{imp} + O_{lit}^{imp} \geq De_{lit}^{imp} \right\} \geq \beta_{lit} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.34)$$

ii. The specific constraints on marine transportation services:

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq \tilde{N}_{ij^*t}^{exp} \cdot \tilde{Cap}_{ij^*}^{exp} - \sum_{l \in L} Y_{ij^*lt}^{exp} - \sum_{l \in L} \sum_{k \in K} Z_{ij^*klt}^{exp} \quad \forall (i, j) \in C_{ij} \wedge j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (6.35)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq \tilde{N}_{j^*it}^{imp} \cdot \tilde{Cap}_{j^*i}^{imp} - \sum_{l \in L} Y_{lj^*it}^{imp} - \sum_{l \in L} \sum_{k \in K} Z_{lkj^*it}^{imp} \quad \forall (j, i) \in C_{ji} \wedge j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (6.36)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq \tilde{N}_{ijt}^{exp} \cdot \tilde{Cap}_{ij}^{exp} \quad \forall (i, j) \in C_{ij} \wedge j \notin D_j, \forall t \in T \quad (6.37)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq \tilde{N}_{jit}^{imp} \cdot \tilde{Cap}_{ji}^{imp} \quad \forall (j, i) \in C_{ji} \wedge j \notin D_j, \forall t \in T \quad (6.38)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq \tilde{N}_{ijt}^{exp} \cdot \tilde{Cap}_{ij}^{exp} + P_{ijt}^{exp} \quad \forall (i, j) \in B_{ij} \wedge j \notin D_j, \forall t \in T \quad (6.39)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq \tilde{N}_{jit}^{imp} \cdot \tilde{Cap}_{ji}^{imp} + P_{jit}^{imp} \quad \forall (j, i) \in B_{ji} \wedge j \notin D_j, \forall t \in T \quad (6.40)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} = R_{ijt}^{exp} \quad \{ \forall (i, j) \in C_{ij} \vee B_{ij} \} \wedge \{ j \in T_j \vee j \notin D_j \}, \forall t \in T \quad (6.41)$$

$$\sum_{l \in L} Y_{ljit}^{imp} = R_{jit}^{imp} \quad \{ \forall (j, i) \in C_{ji} \vee B_{ji} \} \wedge \{ j \in T_j \vee j \notin D_j \}, \forall t \in T \quad (6.42)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} + \sum_{k \in K} \sum_{l \in L} Z_{ijklt}^{exp} \leq \tilde{N}_{ijt}^{exp} \cdot \tilde{Cap}_{ij}^{exp} - \sum_{l \in L} Y_{ij'lt}^{exp} + P_{ijt}^{exp} \quad \forall (i, j) \in C_{ij}, j \in D_j \wedge j \in \gamma_j, j' \in T_j, \forall t \in T \quad (6.43)$$

$$\sum_{l \in L} Y_{ljit}^{imp} + \sum_{k \in K} \sum_{l \in L} Z_{lkjit}^{imp} \leq \tilde{N}_{jit}^{imp} \cdot \tilde{Cap}_{ji}^{imp} - \sum_{l \in L} Y_{lj'it}^{imp} + P_{jit}^{imp} \quad \forall (j, i) \in C_{ji}, j \in D_j \wedge j \in \gamma_j, j' \in T_j, \forall t \in T \quad (6.44)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} + \sum_{k \in K} \sum_{l \in L} Z_{ijklt}^{exp} = R_{ijt}^{exp} + P_{ijt}^{exp} \quad \forall (i, j) \in B_{ij} \vee C_{ij}, j \in D_j, \forall t \in T \quad (6.45)$$

$$\sum_{l \in L} Y_{ljit}^{imp} + \sum_{k \in K} \sum_{l \in L} Z_{lkjit}^{imp} = R_{jit}^{imp} + P_{jit}^{imp} \quad \forall (j, i) \in B_{ji} \vee C_{ji}, j \in D_j, \forall t \in T \quad (6.46)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} + \sum_{k \in K} \sum_{l \in L} Z_{ijklt}^{exp} \leq P_{ijt}^{exp} \quad \forall (i, j) \notin C_{ij}, j \in D_j, \forall t \in T \quad (6.47)$$

$$\sum_{l \in L} Y_{ljit}^{imp} + \sum_{k \in K} \sum_{l \in L} Z_{lkjit}^{imp} \leq P_{jit}^{imp} \quad \forall (j, i) \notin C_{ji}, j \in D_j, \forall t \in T \quad (6.48)$$

$$\sum_{l \in L} Y_{ijlt}^{exp} \leq P_{ijt}^{exp} \quad \forall (i, j) \in L_{ij}, j \notin D_j, \forall t \in T \quad (6.49)$$

$$\sum_{l \in L} Y_{ljit}^{imp} \leq P_{jit}^{imp} \quad \forall (j, i) \in L_{ji}, j \notin D_j, \forall t \in T \quad (6.50)$$

$$R_{ijt}^{exp} / \widetilde{Cap}_{ij}^{exp} = MS_{ijt}^{exp} \quad \forall (i, j) \notin L_{ij}, j \notin \gamma_j, \forall t \in T \quad (6.51)$$

$$R_{jit}^{imp} / \widetilde{Cap}_{ji}^{imp} = MS_{jit}^{imp} \quad \forall (j, i) \notin L_{ji}, j \notin \gamma_j, \forall t \in T \quad (6.52)$$

$$(R_{ijt}^{exp} + R_{ij^*t}^{exp}) / \widetilde{Cap}_{ij^*}^{exp} = MS_{ij^*t}^{exp} \quad \forall (i, j) \notin L_{ij}, j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (6.53)$$

$$(R_{jit}^{imp} + R_{j^*it}^{imp}) / \widetilde{Cap}_{j^*i}^{imp} = MS_{j^*it}^{imp} \quad \forall (j, i) \notin L_{ji}, j \in T_j, j^* \in \gamma_j, \forall t \in T \quad (6.54)$$

$$U_{ijt}^{exp} = R_{ijt}^{exp} / (\widetilde{N}_{ijt}^{exp} \cdot \widetilde{Cap}_{ij}^{exp}) \quad \forall (i, j) \notin L_{ij}, \forall t \in T \quad (6.55)$$

$$U_{jit}^{imp} = R_{jit}^{imp} / (\widetilde{N}_{jit}^{imp} \cdot \widetilde{Cap}_{ji}^{imp}) \quad \forall (j, i) \notin L_{ji}, \forall t \in T \quad (6.56)$$

$$\widetilde{LB}_{ijt}^{exp} \leq U_{ijt}^{exp} \text{ and } \widetilde{LB}_{jit}^{imp} \leq U_{jit}^{imp} \quad \forall (i, j) \notin L_{ij}, \forall t \in T, \forall (j, i) \notin L_{ji} \quad (6.57)$$

iii. The specific constraints on railway transportation services:

$$\sum_{i \in I} \sum_{l \in L} Z_{ijklt}^{exp} \leq S_{jkt}^{exp} \cdot Cap_{jk}^{exp} \quad (j, k) \in C_{jk} \setminus \{T_k\}, \forall t \in T \quad (6.58)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lkjit}^{imp} \leq S_{kjt}^{imp} \cdot Cap_{kj}^{imp} \quad (k, j) \in C_{kj} \setminus \{T_k\}, \forall t \in T \quad (6.59)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{ijklt}^{exp} \leq Pt_{jkt}^{exp} \quad (j, k) \in L_{jk}, \forall t \in T \quad (6.60)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lkjit}^{imp} \leq Pt_{kjt}^{imp} \quad (k, j) \in L_{kj}, \forall t \in T \quad (6.61)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{ijklt}^{exp} \leq S_{jkt}^{exp} \cdot Cap_{jk}^{exp} + Pt_{jkt}^{exp} \quad (j, k) \in B_{jk} \setminus \{T_k\}, \forall t \in T \quad (6.62)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lkjit}^{imp} \leq S_{kjt}^{imp} \cdot Cap_{kj}^{imp} + Pt_{kjt}^{imp} \quad (k, j) \in B_{kj} \setminus \{T_k\}, \forall t \in T \quad (6.63)$$

$$\sum_{i \in I} \sum_{l \in L} Z_{ijk't}^{exp} + \sum_{i \in I} \sum_{l \in G_l} \sum_{k^* \in G_k} Z_{ijk^*t}^{exp} \leq S_{jk't}^{exp} \cdot Cap_{jk'}^{exp} \quad (6.64)$$

$$\forall j \in D_j, \forall k' \in T_k \cap (j, k') \in C_{jk'}, \forall t \in T$$

$$\sum_{i \in I} \sum_{l \in L} Z_{lk'jit}^{imp} + \sum_{i \in I} \sum_{l \in G_l} \sum_{k^* \in G_k} Z_{lk^*jit}^{imp} \leq S_{k'jt}^{imp} \cdot Cap_{k'j}^{imp} \quad (6.65)$$

$$\forall j \in D_j, \forall k' \in T_k \cap (k', j) \in C_{k'j}, \forall t \in T$$

$$\sum_{i \in I} \sum_{j \in D_j} \sum_{l \in G_l} Z_{ijk^*lt}^{exp} \leq Pt_{k'k^*t}^{exp} \quad \forall k' \in T_k, \forall k^* \in G_k \cap (k', k^*) \in L_{k'k^*}, \forall t \in T \quad (6.66)$$

$$\sum_{i \in I} \sum_{j \in D_j} \sum_{l \in G_l} Z_{lk^*jit}^{imp} \leq Pt_{k^*k't}^{imp} \quad \forall k' \in T_k, \forall k \in G_k \cap (k^*, k') \in L_{k^*k'}, \forall t \in T \quad (6.67)$$

$$\widehat{LB}_{jkt}^{exp} \leq S_{jkt}^{exp} \leq \widehat{UB}_{jkt}^{exp} \text{ and } \widehat{LB}_{kjt}^{imp} \leq S_{kjt}^{imp} \leq \widehat{UB}_{kjt}^{imp} \quad \forall (k, j) \notin L_{kj}, \forall (j, k) \notin L_{jk}, \forall t \in T \quad (6.68)$$

$$|S_{jkt}^{exp} - S_{kjt}^{imp}| \leq 1 \quad \forall (k, j) \notin L_{kj}, \forall (j, k) \notin L_{jk}, \forall t \in T \quad (6.69)$$

$$\left| \sum_{t \in T} (S_{jkt}^{exp} - S_{kjt}^{imp}) \right| \leq 1 \quad \forall (k, j) \notin L_{kj}, \forall (j, k) \notin L_{jk} \quad (6.70)$$

The detailed explanations related to the constraints of multi-mode load planning phase of the proposed intermodal fleet planning model have been already given at the Section 5.3 of the previous Chapter 5. It should be noted here that the import/export transport demands of the order countries cannot be known with certainty but have known probability distributions since the freight demands have randomness in nature. Therefore, these demand satisfaction constraints (6.33) and (6.34) are formulated as linear probabilistic restrictions with stochastic right-hand sides. In detail, in order to deal with the freight demand uncertainty, chance-constrained stochastic programming approach is applied which will be presented at the latter sub-section. Furthermore, all of the cost coefficients, transit times, transport capacities of Ro-Ro vessels, maximum number of monthly marine cruises, lower and upper bounds on block train services are also considered as ill-known parameters and represented by triangular fuzzy numbers. In fact, in contrast to probabilistic demand distributions, these parameters are described by possibility distributions since the lack of some information or epistemic uncertainty. In fact, pessimistic, most likely and optimistic values are determined by company experts for the fuzzy parameters based on their knowledge and experience.

Phase-II: Truck & trailer fleet size optimization and fleet allocation.

The constraints of the truck and trailer fleet size optimization, fleet allocation, loaded truck movements and internal empty truck and trailer repositioning issues can be formulated as given by the following Equations (6.71) to (6.103).

iv. Connections between load plans and loaded truck movements:

$$X_{ilt}^{exp} = VE_{ilt}^{exp} + VT_{ilt}^{exp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.71)$$

$$\sum_{i \in I} Y_{ijlt}^{exp} = V_{jlt}^{exp} \quad \forall j \in J, \forall l \in L, \forall t \in T \quad (6.72)$$

$$\sum_{i \in I} \sum_{j \in J} Z_{ijklt}^{exp} = V_{klt}^{exp} \quad \forall k \in K, \forall l \in L, \forall t \in T \quad (6.73)$$

$$X_{lit}^{imp} = VE_{lit}^{imp} + VT_{lit}^{imp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.74)$$

$$\sum_{i \in I} Y_{ljit}^{imp} = V_{ljt}^{imp} \quad \forall j \in J, \forall l \in L, \forall t \in T \quad (6.75)$$

$$\sum_{i \in I} \sum_{j \in J} Z_{lkjlit}^{imp} = V_{lkt}^{imp} \quad \forall k \in K, \forall l \in L, \forall t \in T \quad (6.76)$$

v. The minimum number of European and Turkish plated truck fleet sizes:

$$V_{jlt}^{exp} \cdot \tilde{T}_{jl}^r + V_{ljt}^{imp} \cdot \tilde{T}_{lj}^r + |V_{jlt}^{exp} \cdot \tilde{T}_{jl}^r - V_{ljt}^{imp} \cdot \tilde{T}_{lj}^r| \leq (VS_{jlt}^{exp} + VS_{ljt}^{imp}) \cdot \tilde{\phi}_{lt} \cdot \Gamma \cdot \delta^E \quad (6.77)$$

$$\forall j \in J, \forall l \in L, \forall t \in T$$

$$V_{klt}^{exp} \cdot \tilde{T}_{kl}^r + V_{lkt}^{imp} \cdot \tilde{T}_{lk}^r + |V_{klt}^{exp} \cdot \tilde{T}_{kl}^r - V_{lkt}^{imp} \cdot \tilde{T}_{lk}^r| \leq (VS_{klt}^{exp} + VS_{lkt}^{imp}) \cdot \tilde{\phi}_{lt} \cdot \Gamma \cdot \delta^E \quad (6.78)$$

$$\forall k \in K, \forall l \in L, \forall t \in T$$

$$VE_{ilt}^{exp} \cdot \tilde{T}_{il}^r + VE_{lit}^{imp} \cdot \tilde{T}_{li}^r + |VE_{ilt}^{exp} \cdot \tilde{T}_{il}^r - VE_{lit}^{imp} \cdot \tilde{T}_{li}^r| \leq (EP_{ilt}^{exp} + EP_{lit}^{imp}) \cdot \tilde{\phi}_{lt} \cdot \Gamma \cdot \delta^E \quad (6.79)$$

$$\forall i \in I, \forall l \in L, \forall t \in T$$

$$VT_{ilt}^{exp} \cdot \tilde{T}_{il}^r + VT_{lit}^{imp} \cdot \tilde{T}_{li}^r + |VT_{ilt}^{exp} \cdot \tilde{T}_{il}^r - VT_{lit}^{imp} \cdot \tilde{T}_{li}^r| \leq (TP_{ilt}^{exp} + TP_{lit}^{imp}) \cdot \tilde{\phi}_{lt} \cdot \Gamma \cdot \delta^T \quad (6.80)$$

$$\forall i \in I, \forall l \in L, \forall t \in T$$

vi. The logical constraints for the relationship between loaded truck movements and truck fleet sizes:

$$VS_{jlt}^{exp} \leq V_{jlt}^{exp} \quad \forall j \in J, \forall l \in L, \forall t \in T \quad (6.81)$$

$$VS_{ljt}^{imp} \leq V_{ljt}^{imp} \quad \forall j \in J, \forall l \in L, \forall t \in T \quad (6.82)$$

$$VS_{klt}^{exp} \leq V_{klt}^{exp} \quad \forall k \in K, \forall l \in L, \forall t \in T \quad (6.83)$$

$$VS_{lkt}^{imp} \leq V_{lkt}^{imp} \quad \forall k \in K, \forall l \in L, \forall t \in T \quad (6.84)$$

$$EP_{ilt}^{exp} \leq VE_{ilt}^{exp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.85)$$

$$EP_{lit}^{imp} \leq VE_{lit}^{imp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.86)$$

$$TP_{ilt}^{exp} \leq VT_{ilt}^{exp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.87)$$

$$TP_{lit}^{imp} \leq VT_{lit}^{imp} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.88)$$

vii. The minimum number of trailer fleet size on the overall intermodal logistics network:

$$X_{ilt}^{exp} \cdot \tilde{T}_{li}^r + \sum_{j \in J} Y_{ijlt}^{exp} \cdot (\tilde{T}_{ij}^m + \tilde{T}_{jl}^r) + \sum_{j \in D_j} \sum_{k \in K} Z_{ijklt}^{exp} \cdot (\tilde{T}_{ij}^m + \tilde{T}_{jk}^t + \tilde{T}_{kl}^r) + X_{lit}^{imp} \cdot \tilde{T}_{li}^r +$$

$$\begin{aligned}
& \sum_{j \in J} Y_{ljl}^{imp} \cdot (\tilde{T}_{jl}^m + \tilde{T}_{lj}^r) + \sum_{j \in D_j} \sum_{k \in K} Z_{lkjlt}^{imp} \cdot (\tilde{T}_{ji}^m + \tilde{T}_{kj}^t + \tilde{T}_{lk}^r) + \left| X_{ilt}^{exp} \cdot \tilde{T}_{il} + \sum_{j \in J} Y_{ijlt}^{exp} \cdot (\tilde{T}_{ij}^m + \tilde{T}_{jl}^r) + \right. \\
& \left. \sum_{j \in D_j} \sum_{k \in K} Z_{ijklt}^{exp} \cdot (\tilde{T}_{ij}^m + \tilde{T}_{jk}^t + \tilde{T}_{kl}^r) - X_{lit}^{imp} \cdot \tilde{T}_{li} - \sum_{j \in J} Y_{ljit}^{imp} \cdot (\tilde{T}_{jl}^m + \tilde{T}_{lj}^r) - \right. \\
& \left. \sum_{j \in D_j} \sum_{k \in K} Z_{lkjlt}^{imp} \cdot (\tilde{T}_{ji}^m + \tilde{T}_{kj}^t + \tilde{T}_{lk}^r) \right| \leq (TS_{ilt}^{exp} + TS_{lit}^{imp}) \cdot \tilde{\varphi}_{lt} \cdot \tilde{\Gamma} \cdot \tilde{\varepsilon} \quad \forall i \in I, \forall l \in L, \forall t \in T
\end{aligned} \tag{6.89}$$

viii. The logical constraints for the relationship between loaded trailer movements and trailer fleet sizes:

$$TS_{ilt}^{exp} \leq X_{ilt}^{exp} + \sum_{j \in J} Y_{ijlt}^{exp} + \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{exp} \quad \forall i \in I, \forall l \in L, \forall t \in T \tag{6.90}$$

$$TS_{lit}^{imp} \leq X_{lit}^{imp} + \sum_{j \in J} Y_{ljit}^{imp} + \sum_{j \in J} \sum_{k \in K} Z_{lkjlt}^{imp} \quad \forall i \in I, \forall l \in L, \forall t \in T \tag{6.91}$$

ix. The internal empty truck repositioning constraints:

$$V_{ljl}^{rep} \geq V_{jlt}^{exp} - V_{ljl}^{imp} - VS_{jlt}^{exp} \quad \forall j \in J, \forall l \in L, \forall t \in T \tag{6.92}$$

$$V_{jlt}^{rep} \geq V_{ljl}^{imp} - V_{jlt}^{exp} - VS_{ljl}^{imp} \quad \forall j \in J, \forall l \in L, \forall t \in T \tag{6.93}$$

$$V_{lkt}^{rep} \geq V_{klt}^{exp} - V_{lkt}^{imp} - VS_{klt}^{exp} \quad \forall k \in K, \forall l \in L, \forall t \in T \tag{6.94}$$

$$V_{klt}^{rep} \geq V_{lkt}^{imp} - V_{klt}^{exp} - VS_{lkt}^{imp} \quad \forall k \in K, \forall l \in L, \forall t \in T \tag{6.95}$$

$$VE_{lit}^{rep} \geq VE_{ilt}^{exp} - VE_{lit}^{imp} - EP_{ilt}^{exp} \quad \forall i \in I, \forall l \in L, \forall t \in T \tag{6.96}$$

$$VE_{ilt}^{rep} \geq VE_{lit}^{imp} - VE_{ilt}^{exp} - EP_{lit}^{imp} \quad \forall i \in I, \forall l \in L, \forall t \in T \tag{6.97}$$

$$VT_{lit}^{rep} \geq VT_{ilt}^{exp} - VT_{lit}^{imp} - TP_{ilt}^{exp} \quad \forall i \in I, \forall l \in L, \forall t \in T \tag{6.98}$$

$$VT_{ilt}^{rep} \geq VT_{lit}^{imp} - VT_{ilt}^{exp} - TP_{lit}^{imp} \quad \forall i \in I, \forall l \in L, \forall t \in T \tag{6.99}$$

x. The internal empty trailer repositioning constraints:

$$\begin{aligned}
TR_{lit}^{rep} & \geq X_{ilt}^{exp} + \sum_{j \in J} Y_{ijlt}^{exp} + \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{exp} - X_{lit}^{imp} - \sum_{j \in J} Y_{ljit}^{imp} - \sum_{j \in J} \sum_{k \in K} Z_{lkjlt}^{imp} - TS_{ilt}^{exp} \\
& \quad \forall i \in I, \forall l \in L, \forall t \in T
\end{aligned} \tag{6.100}$$

$$\begin{aligned}
TR_{ilt}^{rep} & \geq X_{lit}^{imp} + \sum_{j \in J} Y_{ljit}^{imp} + \sum_{j \in J} \sum_{k \in K} Z_{lkjlt}^{imp} - X_{ilt}^{exp} - \sum_{j \in J} Y_{ijlt}^{exp} - \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{exp} - TS_{lit}^{imp} \\
& \quad \forall i \in I, \forall l \in L, \forall t \in T
\end{aligned} \tag{6.101}$$

xi. *The logical constraints for the relationship between internal empty truck & trailer repositioning:*

$$VE_{ilt}^{rep} + VT_{ilt}^{rep} \geq TR_{ilt}^{rep} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.102)$$

$$VE_{lit}^{rep} + VT_{lit}^{rep} \geq TR_{lit}^{rep} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.103)$$

The constraints (6.71) - (6.76) yield the connections between the load plans which are generated in the multi-mode load planning phase and loaded truck movements. In other words, the amounts of loaded truck positions between different locations (seaports in Turkey - order countries, seaports in Europe - order countries, railway stations in Europe - order countries etc.) can be computed by using these constraints. It is obvious that only European plated trucks can be used among the seaports in Europe - order countries and rail stations in Europe - order countries. On the other hand, road freight transport operations can be performed by both European and Turkish plated trucks between the seaports in Turkey and order countries. By making use of constraints (6.77) to (6.80), one can calculate the minimum number of truck fleet size that should be available on each transport route of the road network. In detail, truck fleet size on different transport routes are computed with the help of loaded truck positions, road transit times, number of working days at the order countries, truck and trailer availabilities and length (in hours) of the planning period. Actually, these constraints are formulated so as to determine the truck fleet size with different types of plates. For instance, the minimum number of European plated truck fleet size between each railway station and order countries can be obtained from the constraint set (6.78). Fortunately, the provided truck fleet sizes are not only utilized to perform the loaded truck movements at a time period but also realize the internal empty truck repositions in the same time period which can support these loaded truck positions. Additionally, it should be emphasized here that truck fleet sizes are determined by considering the uncertainty of road transit times, truck availabilities and number of working days at the order countries. Because, except the duration of the planning period, all of these parameters cannot be exactly known due to the some sort of ambiguity. Thus, these parameters are also taken as fuzzy data in this truck fleet size optimization and allocation phases. The constraints (6.81) to (6.88) ensure that the number of trucks assigned to any route on the road transport network should be less

and equal to the number of loaded truck positions on the same transport route. Actually, these are the logical constraints for the relationship between the loaded truck positions and fleet size requirement on each transport route. Briefly, since the usage of trucks more than once within the same time period, the truck fleet size on any transport route cannot exceed the loaded truck movements (in positions) on the same route. The trailer fleet size on the overall intermodal logistics network can be calculated by using constraint (6.89). In addition to the road transit times, marine and rail transit times are also incorporated while determining the trailer fleet size. Because, trailers can be transferred by Ro-Ro vessels and block or public trains without their trucks on marine and railway network. For this reason, the trailer fleet size are determined by using the load planning results of the first phase instead of loaded truck movements. On the contrary to truck fleet sizes, we can just calculate the trailer fleet size between the seaports in Turkey and order countries in Europe. In other words, it is not rational to specify the trailer fleet sizes among the intermediate terminals (seaports in Europe and railway stations) and order countries. Because, these are just transshipment points for the trailers and do not correspond to the origins or destinations for the trailer flows. Similar to the constraints (6.81) to (6.88), constraints (6.90) and (6.91) make sure that the number of import and export trailers assigned to any route including marine, rail and road transports cannot pass the number of loaded trailer positions on the same route. Apart from the existing literature on empty vehicle repositioning problems, we divided the repositioning concept for the empty trucks and trailers into two categories namely internal and external. The constraints (6.92)-(6.99) are related to the internal empty truck repositioning problem of the logistics company. In fact, these repositions are resulting from the difference between the import and export loaded truck positions of any given two nodes within the same time period. For instance, the constraints (6.98) and (6.99) present Turkish plated internal empty truck repositioning between seaports in Turkey and order countries. In a similar way, the constraints (6.92) and (6.93) are formulated for European plated internal empty truck repositioning between the seaports in Europe and order countries. For performing the internal empty truck repositions between any given two nodes, it is necessary condition that loaded truck positions must be possible between these nodes. In other words, it is not possible to realize internal empty truck flows among a pair of nodes where there is no loaded truck

positions between them. Thus, the internal empty truck repositions can be conducted between seaports in Europe - order countries, rail stations in Europe - order countries and seaports in Turkey - order countries. Both of the European and Turkish plated trucks can be internally repositioned between the seaports in Turkey and order countries. In summary, the required number of internal empty truck repositions to any given node can be calculated by subtracting the incoming loaded truck positions and truck fleet size of this node from the outgoing loaded truck positions. According to the constraints (6.100) and (6.101), one can calculate the internal empty trailer repositions between the seaports in Turkey and order countries in Europe. Similarly, the incoming/outgoing loaded trailer positions and trailer fleet sizes are utilized while determining the internal empty trailer repositions. These loaded trailer positions are obtained from the first phase of the proposed decision support system for the intermodal fleet planning. In addition, there should be a relationship between the empty truck and trailer repositions. Because, it is supposed that empty trailers can be transferred by using only the road transportation. For this reason, the amounts of European and Turkish plated empty trucks repositioned between the seaports in Turkey and order countries should be greater than the number of empty trailer repositions. In other words, sufficient number of empty trucks should be available for the empty trailer movements as formulated by constraints (6.102) and (6.103).

Phase-III: *Periodic truck & trailer inventories on the intermodal logistics network and fleet expansion/reduction decisions.*

The constraints of periodic truck and trailer inventories on the intermodal logistics network, idle or inactive trucks/trailers awaiting at different locations; fleet expansion and reduction decisions can be formulated as presented by the following Equations (6.104) to (6.125):

xii. *The periodic European & Turkish plated truck inventories at different locations:*

$$\begin{aligned}
 VJ_{jt} = & VJ_{jt-1} + \sum_{l \in L} V_{ljt}^{imp} - \sum_{l \in L} V_{jlt}^{exp} + \sum_{l \in L} V_{ljt}^{rep} - \sum_{l \in L} V_{jlt}^{rep} + \sum_{j' \neq j} VR_{j'jt}^{rep} - \sum_{j' \neq j} VR_{jj't}^{rep} \\
 & + \sum_{k \in K} VR_{kjt}^{rep} - \sum_{k \in K} VR_{jkt}^{rep} + \sum_{l \in L} VR_{ljt}^{rep} - \sum_{l \in L} VR_{jlt}^{rep} \quad \forall j \in J, \forall t \in T
 \end{aligned} \tag{6.104}$$

$$VK_{kt} = VK_{kt-1} + \sum_{l \in L} V_{lkt}^{imp} - \sum_{l \in L} V_{klt}^{exp} + \sum_{l \in L} V_{lkt}^{rep} - \sum_{l \in L} V_{klt}^{rep} + \sum_{k' \neq k} VR_{k'kt}^{rep} - \sum_{k' \neq k} VR_{kk't}^{rep} \quad (6.105)$$

$$+ \sum_{j \in J} VR_{jkt}^{rep} - \sum_{j \in J} VR_{kjt}^{rep} + \sum_{l \in L} VR_{lkt}^{rep} - \sum_{l \in L} VR_{klt}^{rep} \quad \forall k \in K, \forall t \in T$$

$$VL_{lt}^E = VL_{lt-1}^E + \sum_{j \in J} V_{jlt}^{exp} - \sum_{j \in J} V_{ljt}^{imp} + \sum_{k \in K} V_{klt}^{exp} - \sum_{k \in K} V_{lkt}^{imp} + \sum_{i \in I} VE_{ilt}^{exp} - \sum_{i \in I} VE_{lit}^{imp} - \sum_{j \in J} V_{ljt}^{rep} + \sum_{j \in J} V_{jlt}^{rep} - \sum_{k \in K} V_{lkt}^{rep} + \sum_{k \in K} V_{klt}^{rep} - \sum_{i \in I} VE_{lit}^{rep} + \sum_{i \in I} VE_{ilt}^{rep} - \sum_{j \in J} VR_{ljt}^{rep} + \sum_{j \in J} VR_{jlt}^{rep} - \sum_{k \in K} VR_{lkt}^{rep} + \sum_{k \in K} VR_{klt}^{rep} \quad (6.106)$$

$$\sum_{k \in K} VR_{klt}^{rep} - \sum_{l' \neq l} VR_{ll't}^{rep} + \sum_{l' \neq l} VR_{l'l't}^{rep} - \sum_{i \in I} VRE_{lit}^{rep} + \sum_{i \in I} VRE_{ilt}^{rep} \quad \forall l \notin PR_L, \forall t \in T$$

$$VL_{lt}^E = VL_{lt-1}^E + Pr_{lt}^E - Sp_{lt}^E + \sum_{j \in J} V_{jlt}^{exp} - \sum_{j \in J} V_{ljt}^{imp} + \sum_{k \in K} V_{klt}^{exp} - \sum_{k \in K} V_{lkt}^{imp} + \sum_{i \in I} VE_{ilt}^{exp} - \sum_{i \in I} VE_{lit}^{imp} - \sum_{j \in J} V_{ljt}^{rep} + \sum_{j \in J} V_{jlt}^{rep} - \sum_{k \in K} V_{lkt}^{rep} + \sum_{k \in K} V_{klt}^{rep} - \sum_{i \in I} VE_{lit}^{rep} + \sum_{i \in I} VE_{ilt}^{rep} - \sum_{j \in J} VR_{ljt}^{rep} + \sum_{j \in J} VR_{jlt}^{rep} - \sum_{k \in K} VR_{lkt}^{rep} + \sum_{k \in K} VR_{klt}^{rep} - \sum_{l' \neq l} VR_{ll't}^{rep} + \sum_{l' \neq l} VR_{l'l't}^{rep} - \sum_{i \in I} VRE_{lit}^{rep} + \sum_{i \in I} VRE_{ilt}^{rep} \quad (6.107)$$

$$\forall l \in PR_L, \forall t \in T$$

$$VL_{lt}^T = VL_{lt-1}^T + \sum_{i \in I} VT_{ilt}^{exp} - \sum_{i \in I} VT_{lit}^{imp} + \sum_{i \in I} VT_{ilt}^{rep} - \sum_{i \in I} VT_{lit}^{rep} + \sum_{l' \neq l} TTR_{l'lt}^{rep} - \sum_{l' \neq l} TTR_{ll't}^{rep} - \sum_{i \in I} VRT_{lit}^{rep} + \sum_{i \in I} VRT_{ilt}^{rep} \quad \forall l \in L, \forall t \in T \quad (6.108)$$

$$VI_{it}^E = VI_{it-1}^E + \sum_{l \in L} VE_{lit}^{imp} - \sum_{l \in L} VE_{ilt}^{exp} + \sum_{l \in L} VE_{lit}^{rep} - \sum_{l \in L} VE_{ilt}^{rep} + \sum_{l \in L} VRE_{lit}^{rep} - \sum_{l \in L} VRE_{ilt}^{rep} \quad (6.109)$$

$$\forall i \in I, \forall t \in T$$

$$VI_{it}^T = VI_{it-1}^T + \sum_{l \in L} VT_{lit}^{imp} - \sum_{l \in L} VT_{ilt}^{exp} + \sum_{l \in L} VT_{lit}^{rep} - \sum_{l \in L} VT_{ilt}^{rep} + \sum_{l \in L} VRT_{lit}^{rep} - \sum_{l \in L} VRT_{ilt}^{rep} + \sum_{i' \neq i} VRT_{i'it}^{rep} - \sum_{i' \neq i} VRT_{ii't}^{rep} \quad \forall i \notin PR_I, \forall t \in T \quad (6.110)$$

$$VI_{it}^T = VI_{it-1}^T + Pr_{it}^T - Sp_{it}^T + \sum_{l \in L} VT_{lit}^{imp} - \sum_{l \in L} VT_{ilt}^{exp} + \sum_{l \in L} VT_{lit}^{rep} - \sum_{l \in L} VT_{ilt}^{rep} + \sum_{l \in L} VRT_{lit}^{rep} - \sum_{l \in L} VRT_{ilt}^{rep} - \sum_{l \in L} VRT_{lit}^{rep} + \sum_{l' \neq l} VRT_{l'it}^{rep} - \sum_{l' \neq l} VRT_{li't}^{rep} \quad \forall i \in PR_I, \forall t \in T \quad (6.111)$$

xiii. *Periodic trailer inventories at seaports in Turkey & order countries in Europe:*

$$TI_{it} = TI_{it-1} + \sum_{l \in L} X_{lit}^{imp} + \sum_{l \in L} \sum_{j \in J} Y_{ljit}^{imp} + \sum_{l \in L} \sum_{j \in J} \sum_{k \in K} Z_{lkjit}^{imp} - \sum_{l \in L} X_{ilt}^{exp} - \sum_{l \in L} \sum_{j \in J} Y_{ijlt}^{exp} - \sum_{l \in L} \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{exp} + \sum_{l \in L} TR_{lit}^{rep} - \sum_{l \in L} TR_{ilt}^{rep} + \sum_{l \in L} XTR_{lit}^{rep} - \sum_{l \in L} XTR_{ilt}^{rep} + \sum_{l' \neq l} TR_{l'it}^{rep} - \sum_{l' \neq l} TR_{li't}^{rep} \quad (6.112)$$

$$\forall i \notin PR_I, \forall t \in T$$

$$TI_{it} = TI_{it-1} + Prt_{it} - Spt_{it} + \sum_{l \in L} X_{lit}^{imp} + \sum_{l \in L} \sum_{j \in J} Y_{ljit}^{imp} + \sum_{l \in L} \sum_{j \in J} \sum_{k \in K} Z_{lkjit}^{imp} - \sum_{l \in L} X_{ilt}^{exp} - \sum_{l \in L} \sum_{j \in J} Y_{ijlt}^{exp} - \sum_{l \in L} \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{exp} + \sum_{l \in L} TR_{lit}^{rep} - \sum_{l \in L} TR_{ilt}^{rep} + \sum_{l \in L} XTR_{lit}^{rep} - \sum_{l \in L} XTR_{ilt}^{rep} + \sum_{l \in L} TR_{l'it}^{rep} - \sum_{l \in L} TR_{li't}^{rep} \quad (6.113)$$

$$\begin{aligned}
& \sum_{i \in L} \sum_{j \in J} Y_{ijlt}^{exp} - \sum_{i \in L} \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{exp} + \sum_{i \in L} TR_{iit}^{rep} - \sum_{i \in L} TR_{iit}^{rep} + \sum_{i \in L} XTR_{iit}^{rep} - \sum_{i \in L} XTR_{iit}^{rep} + \\
& \quad \sum_{i' \neq i} TR_{i'it}^{rep} - \sum_{i' \neq i} TR_{iit'}^{rep} \quad \forall i \in PR_I, \forall t \in T \\
TL_{lt} = & TL_{lt-1} + \sum_{i \in I} X_{iit}^{exp} + \sum_{i \in I} \sum_{j \in J} Y_{ijlt}^{exp} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{exp} - \sum_{i \in I} X_{iit}^{imp} - \sum_{i \in I} \sum_{j \in J} Y_{ijlt}^{imp} - \\
& \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} Z_{ijklt}^{imp} + \sum_{i \in I} TR_{iit}^{rep} - \sum_{i \in I} TR_{iit}^{rep} + \sum_{i \in I} XTR_{iit}^{rep} - \sum_{i \in I} XTR_{iit}^{rep} + \sum_{i' \neq i} TR_{i'it}^{rep} - \sum_{i' \neq i} TR_{iit'}^{rep} \quad (6.114) \\
& + \sum_{i' \neq i} TTR_{i'it}^{rep} - \sum_{i' \neq i} TTR_{iit'}^{rep} \quad \forall l \in L, \forall t \in T
\end{aligned}$$

xiv. The logical constraints for the relationship between truck & trailer inventory levels and fleet sizes:

$$\begin{aligned}
& \sum_{j \in J} \sum_{l \in L} VS_{jlt}^{exp} + \sum_{j \in J} \sum_{l \in L} VS_{ljt}^{imp} + \sum_{k \in K} \sum_{l \in L} VS_{klt}^{exp} + \sum_{k \in K} \sum_{l \in L} VS_{lkt}^{imp} + \sum_{i \in I} \sum_{l \in L} EP_{ilt}^{exp} + \\
& \sum_{i \in I} \sum_{l \in L} EP_{lit}^{imp} \leq \sum_{j \in J} VJ_{jt-1} + \sum_{k \in K} VK_{kt-1} + \sum_{i \in I} VI_{it-1}^E + \sum_{l \in L} VL_{lt-1}^E \quad \forall t \in T \quad (6.115)
\end{aligned}$$

$$\sum_{i \in I} \sum_{l \in L} TP_{ilt}^{exp} + \sum_{i \in I} \sum_{l \in L} TP_{lit}^{imp} \leq \sum_{i \in I} VI_{it-1}^T + \sum_{l \in L} VL_{lt-1}^T \quad \forall t \in T \quad (6.116)$$

$$\sum_{i \in I} \sum_{l \in L} TS_{ilt}^{exp} + \sum_{i \in I} \sum_{l \in L} TS_{lit}^{imp} \leq \sum_{i \in I} TI_{it-1} + \sum_{l \in L} TL_{lt-1} \quad \forall t \in T \quad (6.117)$$

xv. The idle trucks & trailers awaiting at different locations on the logistics network:

$$IVJ_{jt} = VJ_{jt-1} - \sum_{l \in L} VS_{jlt}^{exp} \quad \forall j \in J, \forall t \in T \quad (6.118)$$

$$IVK_{kt} = VK_{kt-1} - \sum_{l \in L} VS_{klt}^{exp} \quad \forall k \in K, \forall t \in T \quad (6.119)$$

$$IVL_{lt}^E = VL_{lt-1}^E - \sum_{j \in J} VS_{ljt}^{imp} - \sum_{k \in K} VS_{lkt}^{imp} - \sum_{i \in I} EP_{lit}^{imp} \quad \forall l \in L, \forall t \in T \quad (6.120)$$

$$IVL_{lt}^T = VL_{lt-1}^T - \sum_{i \in I} TP_{lit}^{imp} \quad \forall l \in L, \forall t \in T \quad (6.121)$$

$$IVI_{it}^E = VI_{it-1}^E - \sum_{l \in L} EP_{ilt}^{exp} \quad \forall i \in I, \forall t \in T \quad (6.122)$$

$$IVI_{it}^T = VI_{it-1}^T - \sum_{l \in L} TP_{ilt}^{exp} \quad \forall i \in I, \forall t \in T \quad (6.123)$$

$$ITL_{lt} = TL_{lt-1} - \sum_{i \in I} TS_{lit}^{imp} \quad \forall l \in L, \forall t \in T \quad (6.124)$$

$$ITI_{it} = TI_{it-1} - \sum_{l \in L} TS_{ilt}^{exp} \quad \forall i \in I, \forall t \in T \quad (6.125)$$

The constraints (6.104) - (6.111) present the periodic European and Turkish plated truck inventories at different locations on the intermodal logistics network. In detail, constraints (6.104) to (6.107) are formulated to calculate the periodic European plated truck inventories at the seaports in Europe, railway stations and order countries, respectively. In order to compute the truck inventories of any given node at the end of each time period, initial truck inventory levels, outgoing loaded truck positions, incoming loaded truck positions, internal and external empty truck repositions, new truck purchases and sales of second-hand trucks are taken into consideration. While calculating the European plated truck inventories at the order countries, two different formulations are made in constraints (6.106) and (6.107) because of the new truck purchasing and second-hand truck sales policies at these countries. In detail, newly purchased European plated trucks or second-hand trucks can only join to or leave from the network at the pre-specified regions in Germany. Therefore, the truck inventory constraints are formulated by excluding and including these regions of Germany for the new truck purchases and end-of-life truck sales. Constraint (6.108) are designated for the periodic Turkish plated truck inventories at the order countries. Similar to the order countries, both of the European and Turkish plated truck inventories are hold at the seaports in Turkey as given by constraints (6.109) - (6.111). On the other hand, it is assumed that newly purchased Turkish plated trucks or second-hand trucks can join or leave the system at Istanbul only. For this reason, Turkish plated truck inventory constraints are formulated by excluding and including the seaport of Istanbul. The constraints (6.112) – (6.113) reflect the periodic trailer inventory levels at the seaports in Turkey. It should be emphasized here that there is no trailer inventories at the seaports in Europe and rail stations since they are directly transferred from/to these terminals to the order countries or seaports in Turkey. Moreover, new trailer purchases and second-hand trailer sales can be performed at Istanbul only. So, the trailer inventory constraints are formulated as in (6.112) and (6.113) by excluding and including Istanbul seaport, respectively. Finally, one can compute the monthly trailer inventory levels at the order countries by making use of constraint set (6.114). In addition to the initial trailer inventories and loaded trailer movements by road, marine and rail transports; internal and external empty trailer repositions by road transport are also taken into account while determining the periodic trailer inventory levels. The

relationship between the truck and trailer inventories and their fleet sizes are provided by constraints (6.115) to (6.117). These constraints maintain that the amounts of active trucks and trailer at any time period cannot exceed the total inventory levels of trucks or trailer at the end of the previous time period. For instance, as formulated in constraint (6.115) that the number of European plated trucks utilized between the various locations within a month t , cannot goes beyond the total inventory levels of this type of trucks at seaports in Turkey and Europe, railway stations and order countries at the end of the previous time period, $t-1$. Similar restrictions are written for the Turkish plated trucks and trailers in constraints (6.116) and (6.117). It is obvious that Turkish plated truck and trailer inventories are only present at the seaports in Turkey and order countries instead of the transshipment terminals such as the seaports and railway stations in Europe. The number of idle or inactive trucks awaiting at the seaports, railway stations and order countries can be computed by using the constraints (6.18) - (6.123). These idle or inactive trucks can be calculated by subtracting the required fleet sizes at any given time period from the inventory levels of the nodes at the beginning of this time period. For example, number of European plated idle trucks at the seaports in Europe can be calculated by means of constraint (6.118). To do this, the truck fleet which shipped from the seaports to the order countries should be subtracted from the inventory levels of trucks at the seaports in the previous time period. Furthermore, it should be mentioned here that the specified truck fleet size can be utilized for realizing both of the loaded truck positions and internal empty truck repositions. The remaining trucks will be idle or used to perform external empty truck and trailer repositions. Constraints (6.124) and (6.125) are formulated for calculating the number of idle or inactive trailers awaiting at the order countries and seaports in Europe, respectively.

Phase-IV: External empty truck & trailer repositioning issues.

The external empty truck and trailer repositioning constraints and their relationships can be given as in the following Equations (6.126) to (6.147):

xvi. The external European & Turkish plated empty truck repositions:

$$VJ_{j0} \geq \sum_{l \in L} VS_{jlt}^{exp} \quad \forall j \in J, t = 1 \quad (6.126)$$

$$\sum_{j' \neq j} VR_{j'jt-1}^{rep} + \sum_{k \in K} VR_{kjt-1}^{rep} + \sum_{l \in L} VR_{ljt-1}^{rep} \geq \sum_{l \in L} VS_{jlt}^{exp} - VJ_{jt-1} \quad \forall j \in J, t > 1 \quad (6.127)$$

$$VK_{k0} \geq \sum_{l \in L} VS_{klt}^{exp} \quad \forall k \in K, t = 1 \quad (6.128)$$

$$\sum_{k' \neq k} VR_{k'kt-1}^{rep} + \sum_{j \in J} VR_{jkt-1}^{rep} + \sum_{l \in L} VR_{lkt-1}^{rep} \geq \sum_{l \in L} VS_{klt}^{exp} - VK_{kt-1} \quad \forall k \in K, t > 1 \quad (6.129)$$

$$VL_{l0}^E \geq \sum_{j \in J} VS_{ljt}^{imp} + \sum_{k \in K} VS_{lkt}^{imp} + \sum_{i \in I} EP_{lit}^{imp} \quad \forall l \in L, t = 1 \quad (6.130)$$

$$\sum_{j \in J} VR_{jlt-1}^{rep} + \sum_{k \in K} VR_{klt-1}^{rep} + \sum_{l' \neq l} VR_{l'lt-1}^{rep} + \sum_{i \in I} VRE_{ilt-1}^{rep} \geq \quad (6.131)$$

$$\sum_{j \in J} VS_{ljt}^{imp} + \sum_{k \in K} VS_{lkt}^{imp} + \sum_{i \in I} EP_{lit}^{imp} - VL_{lt-1}^E \quad \forall l \in L, t > 1$$

$$VL_{l0}^T \geq \sum_{i \in I} TP_{lit}^{imp} \quad \forall l \in L, t = 1 \quad (6.132)$$

$$\sum_{l' \neq l} TTR_{l'lt-1}^{rep} + \sum_{i \in I} VRT_{ilt-1}^{rep} \geq \sum_{i \in I} TP_{lit}^{imp} - VL_{lt-1}^T \quad \forall l \in L, t > 1 \quad (6.133)$$

$$VI_{i0}^E \geq \sum_{l \in L} EP_{ilt}^{exp} \quad \forall i \in I, t = 1 \quad (6.134)$$

$$\sum_{l \in L} VRE_{ilt-1}^{rep} \geq \sum_{l \in L} EP_{ilt}^{exp} - VI_{it-1}^E \quad \forall i \in I, t > 1 \quad (6.135)$$

$$VI_{i0}^T \geq \sum_{l \in L} TP_{ilt}^{exp} \quad \forall i \in I, t = 1 \quad (6.136)$$

$$\sum_{l \in L} VRT_{ilt-1}^{rep} + \sum_{i' \neq i} VRT_{i'it-1}^{rep} \geq \sum_{l \in L} TP_{ilt}^{exp} - VI_{it-1}^T \quad \forall i \in I, t > 1 \quad (6.137)$$

xvii. The external empty trailer repositions:

$$TL_{l0} \geq \sum_{i \in I} TS_{lit}^{imp} \quad \forall l \in L, t = 1 \quad (6.138)$$

$$\sum_{i \in I} XTR_{ilt-1}^{rep} + \sum_{l' \neq l} TR_{l'lt-1}^{rep} + \sum_{l' \neq l} TTR_{l'lt-1}^{rep} \geq \sum_{i \in I} TS_{lit}^{imp} - TL_{lt-1} \quad \forall l \in L, t > 1 \quad (6.139)$$

$$TI_{i0} \geq \sum_{l \in L} TS_{ilt}^{exp} \quad \forall i \in I, t = 1 \quad (6.140)$$

$$\sum_{l \in L} XTR_{ilt-1}^{rep} + \sum_{l' \neq i} TR_{l'it-1}^{rep} \geq \sum_{l \in L} TS_{ilt}^{exp} - TI_{it-1} \quad \forall i \in I, t > 1 \quad (6.141)$$

xviii. *The logical constraints for the relationship between external empty truck & trailer repositions:*

$$VR_{ll't}^{rep} \geq TR_{ll't}^{rep} \quad \forall l \neq l' \in L, \forall t \in T \quad (6.142)$$

$$VRT_{ii't}^{rep} \geq TR_{ii't}^{rep} \quad \forall i \neq i' \in I, \forall t \in T \quad (6.143)$$

$$VRE_{ilt}^{rep} + VRT_{ilt}^{rep} \geq XTR_{ilt}^{rep} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.144)$$

$$VRE_{lit}^{rep} + VRT_{lit}^{rep} \geq XTR_{lit}^{rep} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.145)$$

xix. *Non-negativity and integrality restrictions of decision variables:*

$$0 \leq U_{ijt}^{exp} \leq 1 \quad \text{and} \quad 0 \leq U_{jit}^{imp} \leq 1 \quad \forall (i, j) \notin L_{ij}, \forall (j, i) \notin L_{ji}, \forall t \in T \quad (6.146)$$

$$X_{ilt}^{exp}, X_{lit}^{imp}, Y_{ijlt}^{exp}, Y_{ljit}^{imp}, Z_{ijklt}^{exp}, Z_{lkjit}^{imp}, O_{ilt}^{exp}, O_{lit}^{imp}, P_{ijt}^{exp}, P_{jit}^{imp}, P_{jkt}^{exp}, P_{kjt}^{imp}, S_{jkt}^{exp}, S_{kjt}^{imp}, \\ P_{k'k^*t}^{exp}, P_{k^*k't}^{imp}, V_{jlt}^{exp}, V_{klt}^{exp}, V_{ljt}^{imp}, V_{lkt}^{imp}, VE_{ilt}^{exp}, VE_{lit}^{imp}, VT_{ilt}^{exp}, VT_{lit}^{exp} \geq 0 \text{ and integer} \quad (6.147)$$

The constraints (6.126) - (6.137) are related to the external European and Turkish plated empty truck repositions. These external repositions are resulted from the different loaded truck positions of a given route in the successive time periods. In detail, the difference between the outgoing fleet size of a node and the truck inventory of this node at the beginning of a time period can be satisfied by the external empty truck repositions of previous time period. In fact, sufficient number of European and/or Turkish plated trucks should be available at any given node in the beginning of the time period. If the required number of outgoing trucks (fleet size) of any given node at a time period are greater than the current truck inventory of that node, the external truck repositions from the other locations on the logistics network to the relevant node are required. Alternatively, when the truck inventory level of any given node is relatively high compared to the needed truck fleet size, this excessive truck inventory can be used to perform external truck repositions from this node to the other locations on the intermodal logistics network. In addition, it is assumed in this chapter that external empty truck repositions of the previous time period can satisfy the truck requirements of the present time period. Thus, it is not possible to realize external empty truck and trailer repositions at the beginning period of the planning horizon. So, sufficient number of trucks should be available at the beginning of the planning horizon so as to use them for loaded truck positions. The constraints (6.126) and (6.127) are formulated for the external European plated empty truck repositions to the

seaports in Europe. According to constraint (6.127), empty trucks can be repositioned from the other seaports in Europe, railway stations and order countries to a seaport in Europe. Similarly, constraints (6.128) and (6.129) are presented for the external European plated empty truck repositions to the railway stations. The constraint (6.129) ensures that external empty truck repositions can be performed from the other railway stations, seaports in Europe and order countries to a railway station. The constraints (6.130) to (6.133) are formulated for the external empty truck repositions to the order countries in Europe. In fact, constraints (6.130) and (6.131) correspond to the empty flows of European plated trucks whereas the constraints (6.132) and (6.133) are related to Turkish plated empty truck repositions to the order countries. According to the constraint (6.131), European plated empty trucks repositioned from the seaports in Turkey and Europe, railway stations and other order countries to any given order country. Between the order countries and seaports in Turkey, both European and Turkish plated empty trucks can be repositioned. The constraint (6.133) maintains that Turkish plated empty trucks can be transferred from the seaports in Turkey and other order countries to any given order country. Besides, Turkish plated trucks are generally repositioned with their empty trailers among the order countries. The constraints (6.134) to (6.137) deal with the external European and Turkish plated empty truck repositions to seaports in Turkey. The constraint (6.134) makes sure that European plated truck inventory at the seaports in Turkey should be adequate at the beginning of the planning horizon so as to perform loaded truck positions between seaports in Turkey and many order countries. According to constraint (6.135), European plated empty trucks can be repositioned from only the order countries to the seaports in Turkey. The constraints (6.136) and (6.137) are formulated for the external empty repositions to the seaports in Turkey by using the Turkish plated trucks. The constraint (6.137) guaranteed that external Turkish plated empty trucks can be transferred from the other seaports in Turkey and order countries to any given seaport in Turkey. In a similar way, the constraints (6.138) - (6.141) are derived for the external empty trailer repositions. In this chapter, it is supposed that empty trailers can be repositioned by only using road transportation. In other words, empty trailers cannot be transferred by the Ro-Ro vessels and block or public trains. According to the constraints (6.138) and (6.140), initial trailer inventory levels at the seaports in Turkey and order countries

should be sufficient in order to conduct the loaded trailer movements through the road, marine and rail transports at the first time period. The external empty trailer repositions can be realized among the order countries themselves, among the seaports themselves in Turkey and also between the seaports in Turkey and order countries. For instance, when the trailer inventory level of an order country at a time period is inadequate, empty trailers can be sent from the other order countries by European or Turkish plated trucks and also from the seaports in Turkey. To do this, constraint (6.139) is formulated to reflect this situation. On the other hand, if the trailer inventory levels at the seaports in Turkey cannot satisfy the required trailer fleet size, empty trailer can be transferred from the other seaports in Turkey and order countries as formulated in constraint (6.141). It should be mentioned here that unlike the internal empty truck and trailer repositioning, it is possible to realize external repositions on the routes which exclude the loaded truck/trailer movements. Constraints (6.142) – (6.145) present the relationship between external empty truck and trailer repositions. Actually, there should be satisfactory amounts of empty trucks so as to realize the empty trailer flows. In other words, amounts of the external empty truck repositions can be at least as much as the empty trailer repositions. Constraint (6.142) insures that empty trailer repositions among the order countries themselves can be performed by using European plated trucks. Similarly, it is warranted by constraint (6.143) that empty trailers can be repositioned among the seaports themselves in Turkey via Turkish plated trucks. Actually, these constraints are derived based on the cabotage limitations. Fortunately, as given by constraints (6.144) and (6.145), both European and Turkish plated trucks can be utilized for the external empty trailer repositions between the order countries and seaports in Turkey. Finally, constraint (6.146) defines lower and upper bounds for decision variables related to the utilizations of the company-owned Ro-Ro vessels and constraint (6.147) preserves the non-negativity of the decision variables and maintains that some of these variables must take integer values. In detail, all of the decision variables related to the load planning phase and the loaded truck/trailer positions are defined as integer. Other variables which represent truck/trailer fleet sizes, empty truck/trailer repositions and regarding inventory levels are stated as continuous.

6.4 A Hybrid Fuzzy & Stochastic Programming Approach to Intermodal Fleet Planning Problem

At the previous section of this chapter, a hybrid fuzzy & stochastic programming model is proposed to an intermodal fleet planning problem for a better reflection of the real-world applications in this area. In fact, most of the real-world fleet planning problems in intermodal transportation may include different types of uncertainties such as randomness, fuzziness and dynamism altogether. However, the greater amounts of researches in the current literature cope with these uncertainty categories independently. In this section, a chance-constrained stochastic programming approach and a well-known fuzzy linear programming method are utilized simultaneously in order to convert the hybrid model into an equivalent auxiliary crisp form.

6.4.1 Chance-Constrained Stochastic Programming Application with LINGO 15.0

Chance-constrained programming is a type of stochastic optimization approach which was first introduced by Charnes and Cooper (1959) to deal with randomness in model parameters by specifying a confidence level. The uncertain model parameters take values from the pre-specified discrete or continuous probability distributions (Liu & Sahinidis, 1996). In this kind of stochastic programming approach, it is assumed that the probabilistic constraints will hold at least p of the time where p presents the confidence or control level. In other words, the probabilistic constraints are generally hold with some probability or reliability level (Birge & Louveaux, 2011). By the way, the term chance corresponds to the probability that the probabilistic constraints are fulfilled (Liu & Iwamura, 1998). In the solution phase, these chance constraints are transformed into equivalent deterministic non-linear forms (Gupta et al., 2013).

In this chapter, it is supposed that the monthly import/export freight demands of the order countries may not be known with certainty, but may have known probability distributions. Given this variability in freight demands, it may not always be practical to satisfy all of the transportation requirements 100 percent of the time. Instead, it is targeted to find a fleet plan which will satisfy the probabilistic freight demand constraints under a pre-specified percentage, i.e., 90 or 95 percent of the time. It makes sure that the generated fleet plans will be feasible for 95% of all instances of the

random freight demands. A linear probabilistic constraint with stochastic right-hand side can be formulated as follows (Bisschop & Roelofs, 2006):

$$Pr\left(\sum_{j \in J} a_j \cdot x_j \geq B\right) \geq 1 - \alpha \quad (6.149)$$

$$\sum_{j \in J} a_j \cdot x_j \geq \hat{B} \quad (6.150)$$

where Pr means that “probability of”, $\hat{B}$ is the critical value and α presents a constant fraction, $\alpha \in [0, 1]$ which characteristically corresponds to the maximum error that is permitted for constraint violation. The probability density function of the random variable B , f_B that is evaluated at α can be depicted as in Figure 6.29.

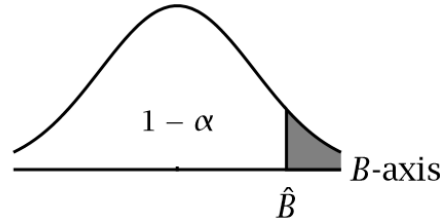


Figure 6.29 Probability density function of a linear probabilistic constraint (Bisschop & Roelofs, 2006)

In fact, the deterministic equivalent form of the above probabilistic constraint can be obtained by computing the critical value of this random right-hand side value. The critical value can be determined by integrating the density function and the inverse cumulative distribution function F_B of the random variable B . An illustrative cumulative distribution function and its inverse can be visualized as in Figure 6.30 (Bisschop & Roelofs, 2006).

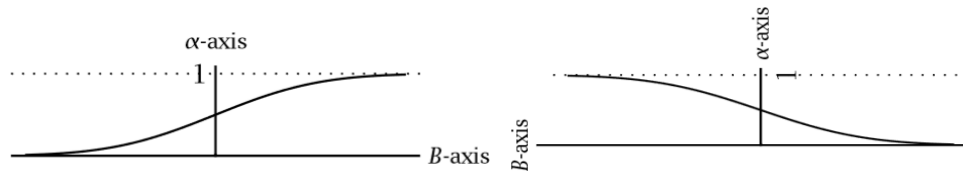


Figure 6.30 Cumulative distribution function of the probabilistic right-hand side and its inverse function

This chapter maintains that total amounts of loads transferred by different modes of transport should meet the random freight demands which are represented by independent continuous random variables with cumulative distributions. The amounts

of import/export freight demands of the order countries are assumed to fit a normal distribution with known means and standard deviations as follows:

$$De_{ilt}^{exp} \sim N(\mu_{ilt}^{exp}, (\sigma_{ilt}^{exp})^2) \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.151)$$

$$De_{lit}^{imp} \sim N(\mu_{lit}^{imp}, (\sigma_{lit}^{imp})^2) \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.152)$$

The import/export demand uncertainties can be taken into account by chance-constrained programming formulations as in Equations (6.33) and (6.34). Then, the deterministic approximation of these probabilistic constraints can be formulated as follows by using the inverse cumulative or quantile function of normal distribution:

$$X_{ilt}^{exp} + \sum_{j \in J} Y_{ijlt}^{exp} + \sum_{j \in D_j} \sum_{k \in K} Z_{ijklt}^{exp} + O_{ilt}^{exp} \geq \zeta_{ilt} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.153)$$

$$\text{Cumulative distribution function: } F(\zeta_{ilt}) = \alpha_{ilt} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.154)$$

$$X_{lit}^{imp} + \sum_{j \in J} Y_{ljit}^{imp} + \sum_{j \in D_j} \sum_{k \in K} Z_{lkjit}^{imp} + O_{lit}^{imp} \geq \psi_{lit} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.155)$$

$$\text{Cumulative distribution function: } F(\psi_{lit}) = \beta_{lit} \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.156)$$

$$\zeta_{ilt} = F^{-1}(\alpha_{ilt} | \mu_{ilt}^{exp}, \sigma_{ilt}^{exp}) = \mu_{ilt}^{exp} + \sigma_{ilt}^{exp} \cdot \sqrt{2} \cdot \text{erf}^{-1}(2 \cdot \alpha_{ilt} - 1) \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.157)$$

$$\psi_{lit} = F^{-1}(\beta_{lit} | \mu_{lit}^{imp}, \sigma_{lit}^{imp}) = \mu_{lit}^{imp} + \sigma_{lit}^{imp} \cdot \sqrt{2} \cdot \text{erf}^{-1}(2 \cdot \beta_{lit} - 1) \quad \forall i \in I, \forall l \in L, \forall t \in T \quad (6.158)$$

where *erf* represents the so-called error function in statistics. The construction of a chance-constrained stochastic programming model with LINGO 15.0 optimization software is composed of the following three main steps (LINDO Systems Inc., 2015):

(i) *Identifying the random variables:*

When building a chance-constrained program, the stochastic components of the model should be first identified. In detail, the values of random variables cannot be known with certainty beforehand. On the other hand, their uncertainty can be expressed with known probability distributions as previously mentioned. While identifying the random variables in LINGO 15, the stage number of the scenario tree where the value of each random variable is revealed should also be yielded. It should be emphasized here that opposite to the other stochastic programming techniques such as multi-stage stochastic programs with recourse, there is only single stage in chance-constrained programming. Thus, the stage value of each random variable must always equal to 1. The @SPSTGRNDV function of LINGO 15.0 is utilized for identifying the

random variables in a chance-constrained programming model. The random variables of the proposed fleet planning model can be identified in LINGO 15.0 as follows:

```
@FOR (DESTINATIONS (L) :@FOR (PERIODS (T) :@FOR (ORIGINS (I) :@SPSTGRNDV (1, DE_IMP (I, L, T) ) ) ) ) ;
@FOR (DESTINATIONS (L) :@FOR (PERIODS (T) :@FOR (ORIGINS (I) :@SPSTGRNDV (1, DE_EXP (L, I, T) ) ) ) ) ;
```

(ii) *Declaring the probability distribution functions of random variables:*

After identifying the stochastic components of the optimization model, the probability distribution functions which the random variables follow should be explained. In general, parametric distributions are declared for the random variables which are defined by a particular type of probability density function, i.e., the normal distribution. Since the freight demands of the order countries follow normal distribution, the @SPDISTNORM (MU, SIGMA, and RNDVAR) function of LINGO 15.0 is used to employ normal distribution to these random variables. In addition, @SPSAMPsize function is also utilized to set sample size for the chance-constrained stochastic program. Actually, this is the sampling frequency or number of times each random variable will be sampled. Since the single stage property of chance-constrained programs, the sample size is always set for this single stage and presents the total number of scenarios. Lastly, the sample size value will be given in the data set of the LINGO model. The normal distribution with means and standard deviations can be defined for both of the import/export freight demands as in the following LINGO code:

```
@FOR (DESTINATIONS (L) :@FOR (PERIODS (T) :@FOR (ORIGINS (I) :
@SPDISTNORM (DE_IMP_MU (I, L, T) , DE_IMP_STD (I, L, T) , DE_IMP (I, L, T) ) ) ) ) ;
@FOR (DESTINATIONS (L) :@FOR (PERIODS (T) :@FOR (ORIGINS (I) :
@SPDISTNORM (DE_EXP_MU (L, I, T) , DE_EXP_STD (L, I, T) , DE_EXP (L, I, T) ) ) ) ) ;
@SPSAMPsize (1, NSAMP) ;
```

(iii) *Identifying chance constraint sets:*

A chance-constrained program may have one or more sets of chance constraints. After the definition of random variables and declaratory of the relevant distributions, each chance constraint set should be identified by involving a name, direction and probability. In order to assign the probabilistic constraints to the chance constraint sets, @SPCHANCE('Set Name', '>=' | '<=', 'Probability') function is utilized in LINGO

15.0. In this section, the probabilistic freight demand satisfaction constraints are named as [IMPORT] and [EXPORT], respectively and coded in LINGO 15.0 as follows:

```
@FOR (DESTINATIONS (L) :@FOR (PERIODS (T) :@FOR (ORIGINS (I) : [IMPORT]
X_IMP (I, L, T) +@SUM (SEMI_INTERMODAL_IMP (I, J, L, T) :Y_IMP (I, J, L, T) ) +
@SUM (INTERMODAL_IMP (I, J, K, L, T) :Z_IMP (I, J, K, L, T) ) +SP_IMP (I, L, T) >=DE_IMP (I, L, T) ;
[EXPORT] X_EXP (L, I, T) +@SUM (SEMI_INTERMODAL_EXP (L, J, I, T) :Y_EXP (L, J, I, T) ) +
@SUM (INTERMODAL_EXP (L, K, J, I, T) :Z_EXP (L, K, J, I, T) ) +SP_EXP (L, I, T) >=DE_EXP (L, I, T) ; ) ) ;
```

In the proposed stochastic fleet planning model, two empty chance constraint row sets are established. Later, these probabilistic demand satisfaction constraints are added to the previously established sets. Moreover, the probability of each chance constraint set should also be given in the data set of the LINGO model.

```
@FOR (DESTINATIONS (L) :@FOR (PERIODS (T) :@FOR (ORIGINS (I) :
@SPCHANCE ('CCP_IMP', IMPORT) ;
@SPCHANCE ('CCP_EXP', EXPORT) ; ) ) ;
@SPCHANCE ('CCP_IMP', '>=', Prb1) ;
@SPCHANCE ('CCP_EXP', '>=', Prb2) ;
```

6.4.2 Application of a Resolution Method to Fuzzy Intermodal Fleet Planning

In this section, interactive resolution method of Jimenez et al. (2007) for linear programming models with fuzzy parameters is selected to transform the proposed fuzzy intermodal fleet planning model into the crisp equivalent form. This method mainly depends on the expected interval, expected value of the fuzzy numbers and as well as the fuzzy ranking procedure of Jimenez (1996) for handling fuzziness embedded into the inequality constraints. In fact, this procedure utilize fuzzy relationship concept for comparison of the fuzzy numbers. Because of the lack of some information and epistemic uncertainty, some of the fleet planning parameters' values cannot be stated precisely and measured easily. In other words, intermodal fleet planning is dynamic and may contain a high degree of imprecision. On the other hand, there is a lack of studies in the fleet management literature which deal with the different sources of uncertainty in an aggregated manner (Peidro et al., 2010). Therefore, the following fleet planning data are considered as ill-known parameters and represented by triangular fuzzy numbers:

- All of the cost parameters, i.e., marine transport costs, rail transport costs, road freight transport costs, outsourcing costs, empty repositioning costs, fixed ownership costs, purchasing costs, selling prices etc.,
- Marine, rail and road transit times between different locations, i.e., seaports, railway terminals, order countries, hubs etc.,
- Number of working days at each month in the order countries of Europe,
- Truck and trailer availabilities in each month (percent of time),
- Transport capacity of company-owned Ro-Ro vessels on different marine link,
- Maximum number of monthly marine cruises that can be performed by the company-owned Ro-Ro vessels,
- Lower bounds on the utilization rates of the company-owned Ro-Ro vessels,
- Lower and upper bounds on the number of block train services on different rail lines at each month.

Actually, these parameters include some sort of ambiguity and can be described by possibility distributions which are derived based on the experience/knowledge of company experts. Actually, these are the fuzzy parameters whose possibility distributions are characterized by triangular fuzzy numbers into the proposed intermodal fleet planning model. The experts of the logistics company defined these triangular fuzzy numbers depending on the deviation percentage of 10% on the crisp values of the parameters. Through the fuzzy intermodal fleet planning model, various alternative fleet plans can be generated with different degrees of satisfaction. The most important reason for choosing the aforementioned interactive resolution method is that one can achieve in a computationally efficient way of solving possibilistic programming problems with its linearity and without any increment in the objective functions and inequality constraints. In other words, it preserves its linearity and model dimension will not increase after the transformation process. Furthermore, this method is able to provide feasible solutions in various degrees of feasibility (α -parametric approach). Thus, it can present α -acceptable optimal solutions which make possible to handle various uncertainty levels. In addition, the fuzzy efficient decision is made iteratively with the participation of the decision maker. Moreover, the decision maker may also have extra information about the risk of violation related to the model constraints. In general, the bigger the feasibility degree is, the worse the objective

function value will be. In other words, the maximum satisfaction degree can be obtained for the goal in case of lower fulfillment level of the constraints (Jiemenez et al. 2007). In this situation, a balanced solution between the feasibility degree of constraints and global satisfaction degree (achievement of aspiration level) of the goal should be found by making use of the greatest membership degree in fuzzy subset of the decision space. A typical fuzzy linear program with equality and inequality constraints can be given as follows:

$$\text{Min } z \cong \tilde{c}^t \cdot x \quad (6.159)$$

Subject to:

$$\tilde{a}_i \cdot x \leq \tilde{b}_i \quad (6.160)$$

$$\tilde{a}_i \cdot x \geq \tilde{b}_i \quad \forall i, i \in \{1, \dots, m\} \quad x \geq 0 \quad (6.161)$$

$$\tilde{a}_i \cdot x \cong \tilde{b}_i \quad (6.162)$$

where $\tilde{c} = (\tilde{c}_1, \tilde{c}_2, \tilde{c}_3, \dots, \tilde{c}_n)$ are the fuzzy coefficients included in the objective function. $\tilde{a} = [\tilde{a}_{ij}]_{m \times n}$ and $\tilde{b} = (\tilde{b}_1, \tilde{b}_2, \tilde{b}_3, \dots, \tilde{b}_m)$ represent fuzzy technological coefficients and fuzzy right hand side values of the constraints, respectively. The transformation process for the above fuzzy mathematical programming model can be realized as in the following α -parametric equivalent auxiliary crisp linear program via the method of Jimenez et al. (2007). After the transformation, this method ensures the equal number of constraints as the deterministic version of the fuzzy model in case of inequality relations. However, two equivalent constraints are needed in case of the equality type constraints (Peidro et al., 2010).

$$\text{Min } EV(\tilde{c}) \cdot x = (E_1^c + E_2^c)/2 \quad (6.163)$$

Subject to:

$$[(1 - \alpha)E_1^{a_i} + \alpha E_2^{a_i}]x \leq \alpha E_1^{b_i} + (1 - \alpha)E_2^{b_i} \quad (6.164)$$

$$[(1 - \alpha)E_2^{a_i} + \alpha E_1^{a_i}]x \geq \alpha E_2^{b_i} + (1 - \alpha)E_1^{b_i} \quad \forall i, i \in \{1, \dots, m\} \quad (6.165)$$

$$\left[\left(1 - \frac{\alpha}{2}\right)E_1^{a_i} + \frac{\alpha}{2}E_2^{a_i}\right]x \leq \frac{\alpha}{2}E_1^{b_i} + \left(1 - \frac{\alpha}{2}\right)E_2^{b_i} \quad x \geq 0, \quad \alpha \in [0,1] \quad (6.166)$$

$$\left[\left(1 - \frac{\alpha}{2}\right)E_2^{a_i} + \frac{\alpha}{2}E_1^{a_i}\right]x \geq \frac{\alpha}{2}E_2^{b_i} + \left(1 - \frac{\alpha}{2}\right)E_1^{b_i} \quad (6.167)$$

where α is a parameter which indicates the feasibility degree of constraints ($\alpha = 0$ unacceptable or most risky solution, $\alpha = 0.5$ neither acceptable nor unacceptable solution, $\alpha = 1.0$ completely acceptable or risk-free solution etc.). Among the α -acceptable fuzzy efficient solutions, a balanced solution between feasibility degree of constraints and satisfaction level of the goal should be chosen with respect to the highest membership degree in the fuzzy set decision as shown by Figure 6.31.

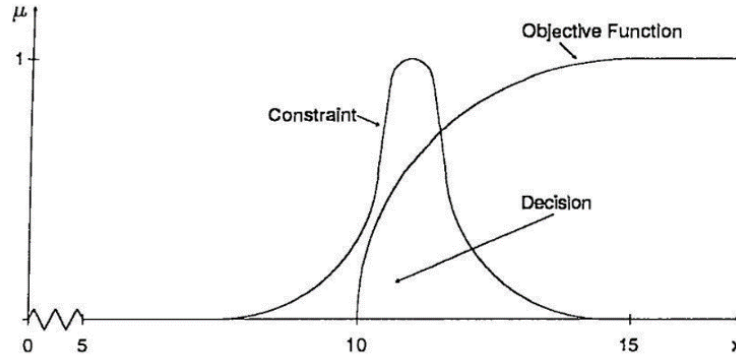


Figure 6.31 A graphical representation of fuzzy decision process (Zimmermann, 1976)

In detail, the fuzzy decision can be defined as follows (Bellman & Zadeh, 1970):

$$\tilde{D} = \tilde{F} \cap \tilde{S} \Rightarrow \mu_D(x) = \mu_F(x) \wedge \mu_S(x) = \min\{\mu_F(x), \mu_S(x)\} = \alpha_k \otimes \mu_S(\alpha_k) \quad (6.168)$$

$$\mu_D(x^*) = \max_{k \in K} \{\alpha_k \otimes \mu_S(\alpha_k)\} \quad (6.169)$$

where $\mu_D(x)$ is membership function of the fuzzy decision set, x^* is the crisp decision and $\otimes$ represents the t -norm (algebraic product) which corresponds to the logical “and” operator or intersection in fuzzy environments (Baykasoğlu & Göçken, 2008). In summary, there is a conflict among the satisfaction degree of goals and fulfilment degree of constraints, so α -acceptable optimal solutions can be achieved. This method aims to provide a balanced solution between the degree of achievement of aspiration levels and the risk of violation of constraints. If the company experts are not satisfied with this balanced solution, they may revise the aspiration level and tolerance threshold value of the fuzzy goal. Subsequently by adopting the resolution method of Jimenez et al. (2007) to the previously formulated fuzzy & stochastic intermodal fleet planning model in Section 6.3 and by representing the uncertain parameters via triangular fuzzy numbers, the following auxiliary crisp equivalent goal and constraints are obtained. For the sake of simplicity, only the first cost component of the total

transport cost objective (6.9), the fourth term of the total CO₂ emission objective and some possibilistic constraints such as (6.37), (6.54), (6.57) (6.68), (6.77) are transformed into the crisp equivalent forms and then the non-fuzzy constraints are added to the fuzzy mathematical model and the remaining unalterable.

Transformation of fuzzy objective function coefficients: uncertain cost and environmental impact terms by using their expected value:

$$\begin{aligned}
 \text{Min } EV(Z1_{marine}) = & \sum_{(i,j) \notin L_{ij}} \sum_{t \in T} R_{ijt}^{exp} \cdot \left(\frac{Co_{ij}^{exp/pes} + 2.Co_{ij}^{exp/mos} + Co_{ij}^{exp/opt}}{4} \right) + \\
 & \sum_{(j,i) \notin L_{ji}} \sum_{t \in T} R_{jit}^{imp} \cdot \left(\frac{Co_{ji}^{imp/pes} + 2.Co_{ji}^{imp/mos} + Co_{ji}^{imp/opt}}{4} \right) + \\
 & \sum_{(i,j) \notin C_{ij}} \sum_{t \in T} P_{ijt}^{exp} \cdot \left(\frac{Cp_{ij}^{exp/pes} + 2.Cp_{ij}^{exp/mos} + Cp_{ij}^{exp/opt}}{4} \right) + \\
 & \sum_{(j,i) \notin C_{ji}} \sum_{t \in T} P_{jit}^{imp} \cdot \left(\frac{Cp_{ji}^{imp/pes} + 2.Cp_{ji}^{imp/mos} + Cp_{ji}^{imp/opt}}{4} \right)
 \end{aligned} \tag{6.170}$$

$$\begin{aligned}
 \text{Min } EV(Z3_{outsourcing}) = & \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} o_{ilt}^{exp} \cdot \left[\left(\frac{\varphi_{pes}^{out} + 2.\varphi_{mos}^{out} + \varphi_{opt}^{out}}{4} \right) \cdot d_{il}^r \cdot \left(\frac{CO2_{pes}^R + 2.CO2_{mos}^R + CO2_{opt}^R}{4} \right) \right. \\
 & + \left(1 - \frac{\varphi_{pes}^{out} + 2.\varphi_{mos}^{out} + \varphi_{opt}^{out}}{4} \right) \cdot \left(\sum_{j \in J} d_{ij}^m \cdot \left(\frac{CO2_{pes}^M + 2.CO2_{mos}^M + CO2_{opt}^M}{4} \right) + \right. \\
 & \left. \left. d_{jl}^r \cdot \left(\frac{CO2_{pes}^R + 2.CO2_{mos}^R + CO2_{opt}^R}{4} \right) \right) \right] \\
 & + \sum_{i \in I} \sum_{l \in L} \sum_{t \in T} o_{lit}^{imp} \cdot \left[\left(\frac{\varphi_{pes}^{out} + 2.\varphi_{mos}^{out} + \varphi_{opt}^{out}}{4} \right) \cdot d_{li}^r \cdot \left(\frac{CO2_{pes}^R + 2.CO2_{mos}^R + CO2_{opt}^R}{4} \right) \right. \\
 & + \left(1 - \frac{\varphi_{pes}^{out} + 2.\varphi_{mos}^{out} + \varphi_{opt}^{out}}{4} \right) \cdot \left(\sum_{j \in J} d_{lj}^r \cdot \left(\frac{CO2_{pes}^R + 2.CO2_{mos}^R + CO2_{opt}^R}{4} \right) \right. \\
 & \left. \left. + d_{ji}^m \cdot \left(\frac{CO2_{pes}^M + 2.CO2_{mos}^M + CO2_{opt}^M}{4} \right) \right) \right]
 \end{aligned} \tag{6.171}$$

Transformation of fuzzy technological coefficients and right-hand side values of constraints by their expected interval and fuzzy ranking procedure of Jimenez (1996):

$$\begin{aligned}
 \sum_{l \in L} Y_{ijlt}^{exp} \leq & \alpha \left(\frac{N_{ijt}^{exp/pes} + N_{ijt}^{exp/mos}}{2} \right) \left(\frac{Cap_{ij}^{exp/pes} + Cap_{ij}^{exp/mos}}{2} \right) + \\
 (1 - \alpha) & \left(\frac{N_{ijt}^{exp/mos} + N_{ijt}^{exp/opt}}{2} \right) \left(\frac{Cap_{ij}^{exp/mos} + Cap_{ij}^{exp/opt}}{2} \right) \quad \forall (i,j) \in C_{ij} \wedge j \notin D_j, \forall t \in T
 \end{aligned} \tag{6.172}$$

$$R_{jit}^{imp} + R_{j^*it}^{imp} \leq \frac{\alpha}{2} \left(\frac{Cap_{ji}^{imp/pes} + Cap_{ji}^{imp/mos}}{2} \right) MS_{j^*it}^{imp} + \left(1 - \frac{\alpha}{2} \right) \left(\frac{Cap_{ji}^{imp/mos} + Cap_{ji}^{imp/opt}}{2} \right) MS_{j^*it}^{imp} \quad (6.173)$$

$$\forall (j, i) \notin L_{ji}, j \in T_j, j^* \in \gamma_j, \forall t \in T$$

$$R_{jit}^{imp} + R_{j^*it}^{imp} \geq \frac{\alpha}{2} \left(\frac{Cap_{ji}^{imp/mos} + Cap_{ji}^{imp/opt}}{2} \right) . MS_{j^*it}^{imp} + \left(1 - \frac{\alpha}{2} \right) \left(\frac{Cap_{ji}^{imp/pes} + Cap_{ji}^{imp/mos}}{2} \right) . MS_{j^*it}^{imp} \quad (6.174)$$

$$\forall (j, i) \notin L_{ji}, j \in T_j, j^* \in \gamma_j, \forall t \in T$$

$$U_{jit}^{imp} \geq \alpha \left(\frac{LB_{jit}^{imp/mos} + LB_{jit}^{imp/opt}}{2} \right) + (1 - \alpha) \left(\frac{LB_{jit}^{imp/pes} + LB_{jit}^{imp/mos}}{2} \right) \quad \forall (j, i) \notin L_{ji}, \forall t \in T \quad (6.175)$$

$$S_{jkt}^{exp} \geq \alpha \left(\frac{LB_{jkt}^{exp/mos} + LB_{jkt}^{exp/opt}}{2} \right) + (1 - \alpha) \left(\frac{LB_{jkt}^{exp/pes} + LB_{jkt}^{exp/mos}}{2} \right) \quad \forall (j, k) \notin L_{jk}, \forall t \in T \quad (6.176)$$

$$\in T$$

$$S_{jkt}^{exp} \leq \alpha \left(\frac{UB_{jkt}^{exp/pes} + UB_{jkt}^{exp/mos}}{2} \right) + (1 - \alpha) \left(\frac{UB_{jkt}^{exp/mos} + UB_{jkt}^{exp/opt}}{2} \right) \quad \forall (j, k) \notin L_{jk}, \forall t \in T \quad (6.177)$$

$$\begin{aligned} & V_{jit}^{exp} \cdot \left\{ \alpha \left(\frac{T_{jl}^{r/opt}}{2} \right) + (1 - \alpha) \left(\frac{T_{jl}^{r/pes} + T_{jl}^{r/mos}}{2} \right) \right\} + \\ & V_{ljt}^{imp} \cdot \left\{ \alpha \left(\frac{T_{lj}^{r/mos} + T_{lj}^{r/opt}}{2} \right) + (1 - \alpha) \left(\frac{T_{lj}^{r/pes} + T_{lj}^{r/mos}}{2} \right) \right\} + \\ & \left| V_{jlt}^{exp} \cdot \left\{ \alpha \left(\frac{T_{jl}^{r/mos} + T_{jl}^{r/opt}}{2} \right) + (1 - \alpha) \left(\frac{T_{jl}^{r/pes} + T_{jl}^{r/mos}}{2} \right) \right\} - \right. \\ & \left. V_{ljt}^{imp} \cdot \left\{ \alpha \left(\frac{T_{lj}^{r/mos} + T_{lj}^{r/opt}}{2} \right) + (1 - \alpha) \left(\frac{T_{lj}^{r/pes} + T_{lj}^{r/mos}}{2} \right) \right\} \right| \leq (VS_{jlt}^{exp} + VS_{ljt}^{imp}). \\ & \Gamma \cdot \left\{ \alpha \left(\frac{\phi_{lt}^{pes} + \phi_{lt}^{mos}}{2} \right) \left(\frac{\delta^{E/pes} + \delta^{E/mos}}{2} \right) + (1 - \alpha) \left(\frac{\phi_{lt}^{mos} + \phi_{lt}^{opt}}{2} \right) \left(\frac{\delta^{E/mos} + \delta^{E/opt}}{2} \right) \right\} \\ & \forall j \in J, \forall l \in L, \forall t \in T \end{aligned} \quad (6.178)$$

6.5 Computational Results of Real-Life Application in Turkish Logistics Industry

6.5.1 Company Introduction and Description of Uncertain Data

In this section, in order to show performance of the proposed holistic intermodal fleet planning model, it is illustrated through a real-life application in EKOL Logistics Inc. which is a large-sized international logistics company of Turkey. It has been also mentioned lots of information about EKOL logistics Inc. in Section 5.4 of Chapter 5. Furthermore, additional data related to the total number of employees, total facility area, annual growth rates, sales and investment amounts are demonstrated by the following Figures 6.32 to 6.35 for better reflection of the company's size.

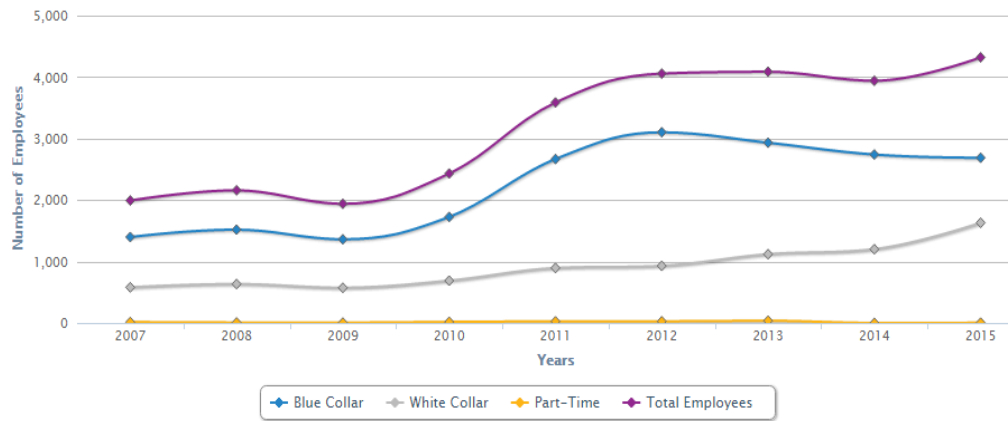


Figure 6.32 Number of employees of the logistics company within Turkey (EKOL, 2015)

In addition to Turkish employees which is depicted in Figure 6.32, the company have also approximately 1239 employees in 12 different countries of Europe. Moreover, there are also 100.000 sqm warehousing area in 12 different countries across Europe besides the facility area in Turkey that is depicted in below Figure 6.33.

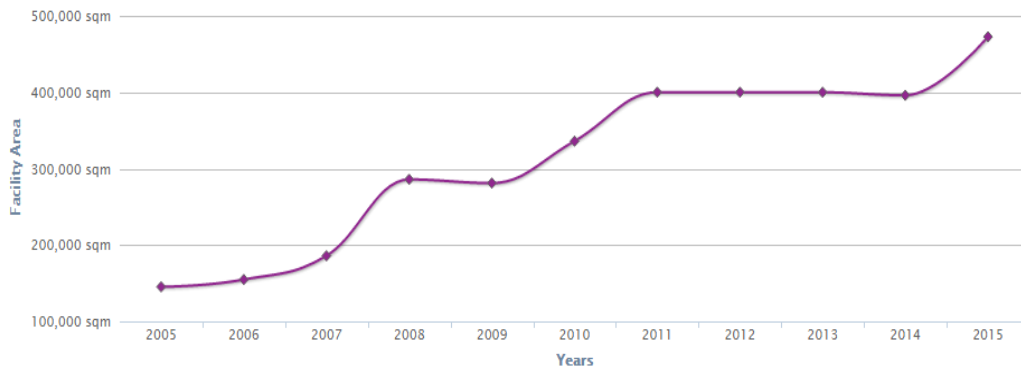


Figure 6.33 Size of facility area belonging to the logistics company in Turkey (EKOL, 2015)

According to Figures 6.32 and 6.33, it is noted that total number of employees and warehousing area of the logistics company increase regularly over the years. On the other hand, as depicted in Figure 6.34, the annual growth rate of the company may fluctuate in value despite of the increasing sales amounts. This may also lead to decreases in the investment amounts which is also seen from Figure 6.35. Fortunately, both of the grow rates and investment amounts tend to increase rapidly in recent years.



Figure 6.34 Annual grow rates of the logistics company over the past eight years (EKOL, 2015)

As mentioned previously, EKOL Logistics Inc. performs international transportation services all over Europe. The market shares of EKOL Logistics Inc. at different countries can be shown by the following Figures 6.36 to 6.38. It should be highlighted that these market share values just involve international freight data which is obtained from international forwarding association in Turkey (UND, 2016). It is obvious that market shares of the company at Ireland, Switzerland, Luxembourg, Czech Republic, Italy, Slovenia, Croatia and Bulgaria are increased in 2016.

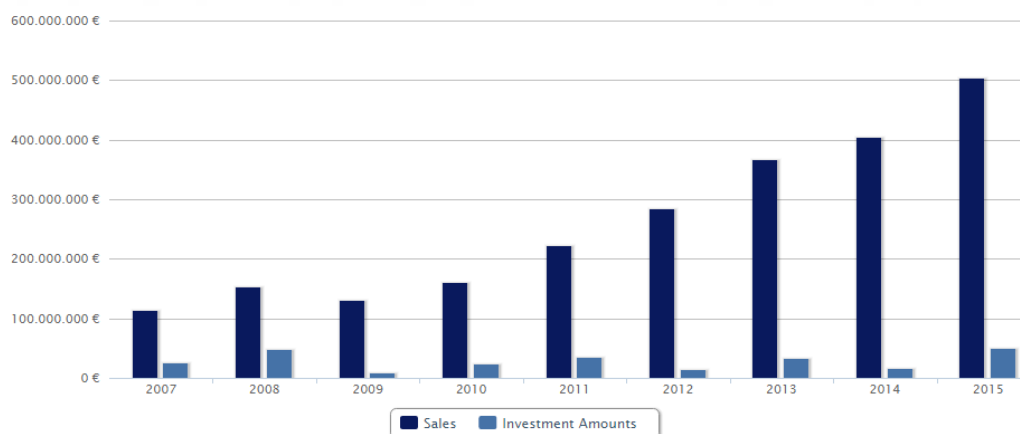


Figure 6.35 Amounts of the sales and investments over the past nine years (EKOL, 2015)

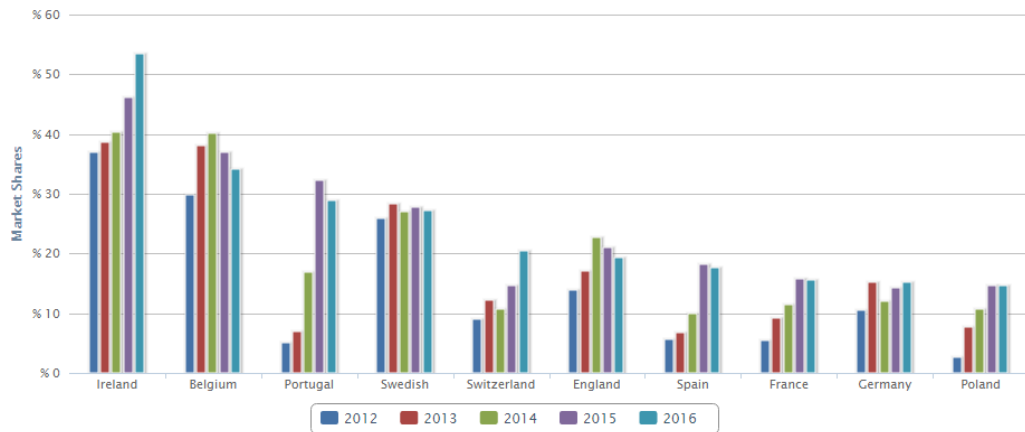


Figure 6.36 Market shares of the logistics company at different order countries (EKOL, 2016)

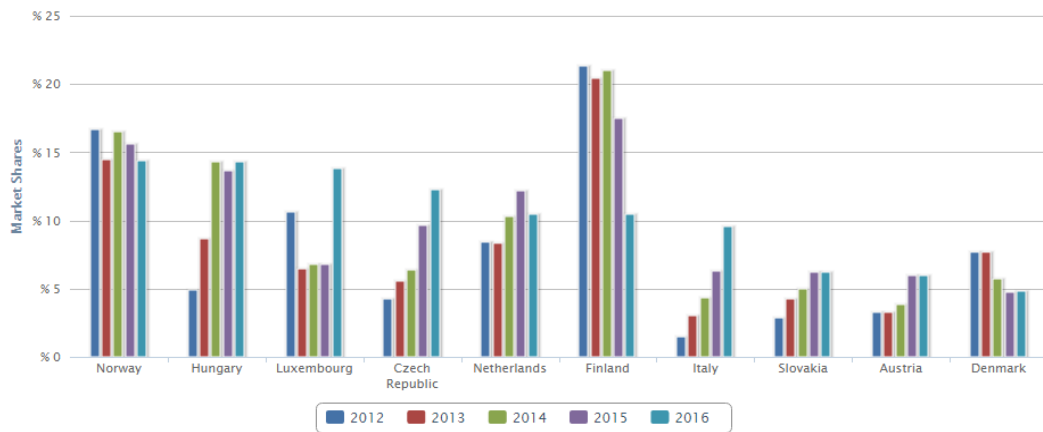


Figure 6.37 Market shares of the logistics company at different order countries of Europe

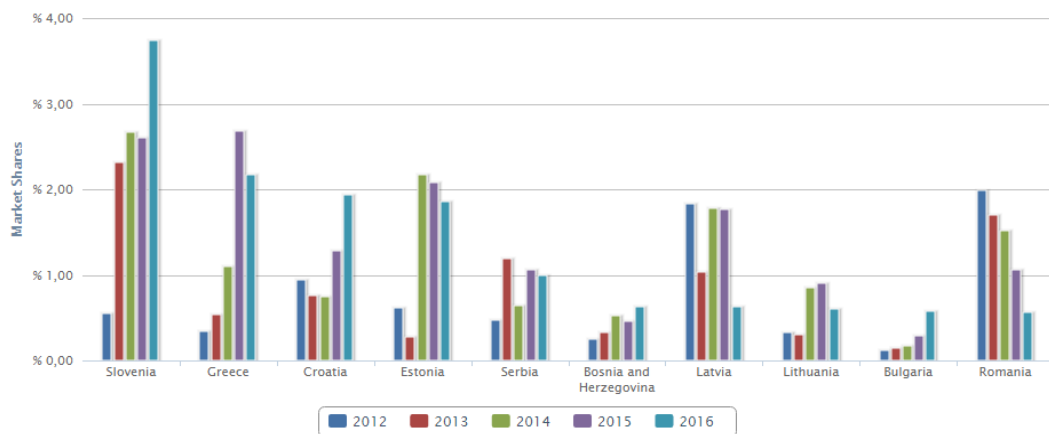


Figure 6.38 Market shares of the logistics company at different order countries of Europe

Moreover, EKOL Logistics desires to reduce the mileage on road by making use of its intermodal transportation services and minimize the carbon dioxide, hydrocarbon, particle and nitrogen emissions. The total carbon dioxide emission reduction and diesel savings in the first quarter of 2016 are displayed in Figure 6.39.

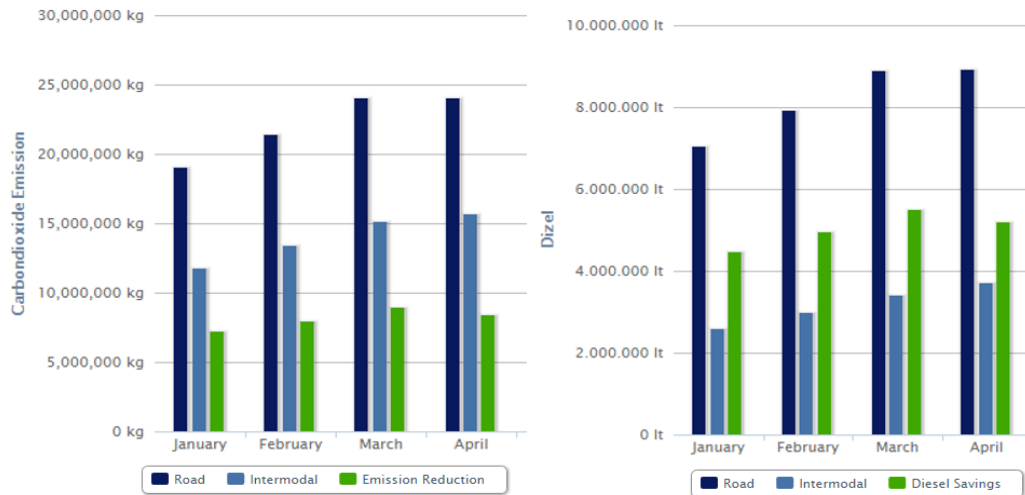


Figure 6.39 Environmental data: CO₂ emission reduction and diesel savings in 2016 (EKOL, 2016)

The data ranges utilized in the real-life case study were previously presented in Table 5.4 of Chapter 5. But, these data is also elaborated by the following Tables 6.7 to 6.13 in order to present the uncertain parameters in a more detailed manner. It should be emphasized here the data related to the real-life case study is manipulated by multiplying all of the values with a specific ratio because of the confidential information policy of the logistics company. In Table 6.7, fixed ownership costs, purchasing costs for new trucks/trailers and sales prices of second-hand trucks/trailers are given. While calculating the ownership costs which are used to determine the appropriate fleet size, the lifetime of the trucks/trailers, initial investment amounts and the regarding final scrap value are also taken into account. In Table 6.8, the triangular fuzzy numbers which are related to the marine and railway transportation costs, transport capacities and transit times are presented for each marine link or rail line. On the contrary to transport capacity of Ro-Ro vessels, it is assumed that block trains have limited crisp transport capacity. Additionally, there is no limitation on transportation capacity of the other logistics service providers' Ro-Ro vessels and public trains. On the other hand, these alternative marine and railway transportation services are more expensive than the services by company-owned Ro-Ro vessels and block trains. The marine and rail transit times between the terminals are also given in Table 6.8.

Table 6.7 Fuzzy ownership, purchasing costs and sales prices of trucks and trailers

	Trailers	European plated trucks	Turkish plated trucks
Ownership cost (€)	(200, 300, 500)	(1700, 2000, 2300)	(1500, 1700, 1900)
Purchasing cost (€)	(20000, 30000, 35000)	(120000, 150000, 180000)	(100000, 120000, 140000)
Sales price (€)	(10000, 15000, 20000)	(60000, 75000, 90000)	(50000, 60000, 70000)

Table 6.8 Fuzzy transport costs, capacities and bounds in railway and marine transportation

By company-owned Ro-Ro vessels (€/trailer)	Transportation costs (€/trailer)	Transport capacity (trailer)	Marine and rail transit times (hrs.)
Istanbul - Lavrion	(450, 475, 500)	(200, 240, 250)	(15, 19, 22)
Istanbul - Trieste	(700, 750, 800)	(200, 240, 250)	(60, 63.75, 65)
Izmir - Sete	(1000, 1400, 1500)	(150, 165, 200)	(40, 48, 52)
By other logistics service providers' Ro-Ro vessels (€/trailer)			
Istanbul - Trieste	(750, 760, 800)	Unlimited	(60, 63.75, 65)
Istanbul - Toulon	(900, 918, 950)	Unlimited	(72, 88, 90)
Izmir - Trieste	(630, 648, 700)	Unlimited	(60, 72, 80)
Mersin Trieste	(750, 787, 820)	Unlimited	(90, 96, 100)
Railway trips by block trains (€/trip)			
Trieste - Ostrava	(16000, 16608, 17000)	28	(20, 24, 26)
Trieste - Ludwigshafen	(20000, 20256, 21000)	32	(17, 20, 22)
Trieste - Cologne	(23000, 23328, 24000)	32	(20, 24, 26)
Railway trips by public trains (€/trailer)			
Trieste - Munich	(650, 685, 700)	Unlimited	(18, 22, 24)
Cologne - Malmö	(650, 685, 700)	Unlimited	(20, 22, 24)
Cologne - Gothenburg	(650, 685, 700)	Unlimited	(20, 22, 24)

These are also represented by the triangular fuzzy numbers because of the uncertainty in travel times, awaiting times at the terminals and availabilities of the Ro-Ro vessels, block and public trains. Other fuzzy data related to the environmental impact values, composition of the outsourcing option, truck/trailer availabilities, number of working days at the order countries, loaded/empty road transportation costs etc. are delivered in Table 6.9. Tables 6.10 and 6.11 provided fuzzy upper bounds on the number of marine cruises by company-owned Ro-Ro vessels and maximum number of monthly railway trips by block trains. Finally, means and standard deviations of the normally distributed import/export freight demands of the order countries for each month are presented in Tables 6.12 and 6.13, respectively.

Table 6.9 Other fuzzy data on environmental impact values, outsourcing option, availabilities etc.

Uncertain parameters	Triangular fuzzy number
CO ₂ emission value by road freight transportation (kg/km)	(0.8, 0.918, 1.0)
CO ₂ emission value by marine transportation (kg/km)	(0.3, 0.357, 0.5)
CO ₂ emission value by railway transportation (kg/km)	(0, 0.05, 0.1)
CO ₂ emission value by empty truck repositioning (kg/km)	(0.8, 0.85, 0.9)
Ratio of road freight transportation for outsourcing option (%)	(0.7, 0.75, 0.8)
Ratio of combined marine and road transports for outsourcing option (%)	(0.2, 0.25, 0.3)
Number of monthly working days at the order countries (day/month)	(20, 25, 28)
Availability rate for trailers (%)	(60, 70, 90)
Availability rate for European plated trucks (%)	(60, 70, 90)
Availability rate for Turkish plated trucks (%)	(60, 70, 90)
Lower bounds on the number of block train services (trip/month)	(6, 8, 10)
Road freight transportation cost for a unit of loaded trailer (€/km)	(1.1, 1.2, 1.3)
Road freight transportation cost for a unit of empty trailer (€/km)	(1, 1.1, 1.2)
Road freight transportation cost for a unit of empty truck (€/km)	(0.8, 1.0, 1.1)

Table 6.10 The maximum number of import/export marine cruises by the company of Ro-Ro vessels in each month

Export	December 2015	January 2016	February	March	April	May	June	July	August	September	October	November
Istanbul - Lavrion	(3, 4, 6)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)
Istanbul - Trieste	(10, 13, 15)	(10, 12, 14)	(10, 13, 15)	(10, 13, 15)	(11, 14, 16)	(10, 12, 15)	(11, 14, 16)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)
Izmir - Sete	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)
Import												
Lavrion - Istanbul	(6, 9, 11)	(6, 8, 10)	(7, 9, 11)	(7, 9, 11)	(6, 8, 10)	(7, 9, 11)	(7, 9, 11)	(7, 9, 11)	(6, 8, 10)	(7, 9, 11)	(7, 9, 11)	(7, 9, 11)
Trieste - Istanbul	(11, 14, 16)	(10, 12, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(11, 14, 16)	(10, 12, 14)	(11, 14, 16)	(10, 13, 15)	(10, 13, 15)
Sete - Izmir	(4, 5, 7)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(3, 4, 6)	(4, 5, 7)	(3, 4, 6)	(4, 5, 7)

Table 6.11 The maximum number of import/export railway trips by the block trains in each month

Export	December 2015	January 2016	February	March	April	May	June	July	August	September	October	November
Trieste - Ostrava	(11, 14, 16)	(10, 12, 14)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(11, 14, 16)	(10, 12, 14)	(11, 14, 16)	(10, 13, 15)	(10, 13, 15)
Trieste - Ludwigshafen	(25, 27, 30)	(22, 24, 27)	(23, 26, 29)	(23, 26, 29)	(24, 27, 30)	(22, 25, 28)	(24, 27, 30)	(23, 26, 29)	(23, 26, 29)	(24, 27, 30)	(22, 25, 28)	(24, 27, 30)
Trieste - Cologne	(34, 39, 42)	(31, 36, 39)	(35, 40, 43)	(34, 39, 42)	(34, 39, 42)	(34, 39, 42)	(35, 40, 43)	(35, 40, 43)	(34, 39, 42)	(34, 39, 42)	(34, 39, 42)	(35, 40, 43)
Import												
Ostrava - Trieste	(11, 14, 16)	(10, 12, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(10, 13, 15)	(11, 14, 16)	(10, 13, 15)	(11, 14, 16)
Ludwigshafen - Trieste	(24, 27, 30)	(21, 24, 27)	(23, 26, 29)	(23, 26, 29)	(23, 26, 29)	(23, 26, 29)	(24, 27, 30)	(23, 26, 29)	(23, 26, 29)	(24, 27, 30)	(22, 25, 28)	(24, 27, 30)
Cologne - Trieste	(35, 40, 42)	(31, 36, 39)	(34, 39, 42)	(34, 39, 42)	(34, 39, 42)	(34, 39, 42)	(36, 41, 43)	(34, 39, 42)	(34, 39, 42)	(35, 40, 43)	(33, 38, 41)	(35, 40, 43)

Table 6.12 Mean values and standard deviations of the probabilistic export freight demands (in positions) of the order countries

Origin	Destination	December 2015	January 2016	February	March	April	May	June	July	August	September	October	November
Istanbul	Germany Region-1	23/2	26/2	26/2	26/2	26/2	26/2	26/2	25/2	21/2	27/2	28/2	28/2
Istanbul	Germany Region-2	15/1	17/1	16/1	18/1	16/1	17/1	16/1	16/1	14/1	17/1	17/1	18/1
Istanbul	Germany Region-3	99/9	106/10	108/10	104/10	99/9	99/9	100/10	108/10	79/7	97/9	124/12	125/12
Istanbul	Germany Region-4	148/14	175/17	138/13	139/13	133/13	134/13	139/13	132/13	125/12	142/14	210/21	181/18
Istanbul	Germany Region-5	77/7	77/7	74/7	79/7	75/7	77/7	79/7	75/7	70/7	79/7	81/8	83/8
Istanbul	Germany Region-6	128/12	138/13	131/13	143/14	136/13	141/14	142/14	139/13	132/13	147/14	150/15	163/16
Istanbul	Germany Region-7	140/14	156/15	139/13	155/15	140/14	169/16	156/15	174/17	137/13	162/16	155/15	147/14
Istanbul	Germany Region-8	247/24	294/29	291/29	297/29	295/29	298/29	293/29	293/29	280/28	294/29	296/29	298/29
Istanbul	Germany Region-9	74/7	92/9	94/9	94/9	94/9	95/9	95/9	93/9	80/8	92/9	94/9	93/9
Istanbul	Germany Region-10	81/8	73/7	36/3	43/4	38/3	42/4	38/3	38/3	30/3	44/4	116/11	92/9
Istanbul	France Region-1	14/1	15/1	14/1	15/1	12/1	13/1	15/1	13/1	13/1	17/1	17/1	17/1
Istanbul	France Region-2	44/4	40/4	34/3	39/3	39/3	38/3	44/4	37/3	39/3	51/5	51/5	50/5
Istanbul	France Region-3	174/17	205/20	216/21	200/20	212/21	226/22	223/22	160/16	142/14	200/20	224/22	229/22
Istanbul	France Region-4	49/4	48/4	48/4	51/5	47/4	48/4	57/5	50/5	42/4	60/6	60/6	58/5
Istanbul	Greece	35/3	37/3	36/3	40/4	38/3	40/4	38/3	39/3	17/1	40/4	38/3	39/3
Istanbul	Portugal	3/0	4/0	4/0	5/0	4/0	4/0	4/0	3/0	3/0	4/0	4/0	5/0
Istanbul	Spain	98/9	158/15	120/12	136/13	156/15	160/16	138/13	147/14	101/10	145/14	143/14	134/13
Istanbul	England	306/30	245/24	256/25	276/27	299/29	292/29	298/29	313/31	265/26	291/29	321/32	325/32
Istanbul	Belgium	119/11	142/14	142/14	128/12	134/13	138/13	155/15	138/13	122/12	125/12	120/12	134/13
Istanbul	Slovenia	15/1	16/1	15/1	17/1	15/1	16/1	15/1	17/1	11/1	16/1	16/1	18/1
Istanbul	Austria	48/4	48/4	47/4	52/5	54/5	54/5	41/4	45/4	42/4	39/3	49/4	46/4
Istanbul	Hungary	85/8	105/10	101/10	104/10	93/9	98/9	101/10	84/8	76/7	90/9	101/10	100/10
Istanbul	Italy	206/20	217/21	215/21	212/21	216/21	213/21	223/22	213/21	165/16	222/22	220/22	216/21
Istanbul	Finland	6/0	6/0	6/0	7/0	6/0	7/0	7/0	7/0	6/0	7/0	6/0	7/0
Istanbul	Slovakia	20/2	26/2	25/2	24/2	26/2	26/2	24/2	22/2	22/2	22/2	24/2	23/2
Istanbul	Czech Republic	51/5	73/7	68/6	64/6	67/6	72/7	62/6	66/6	62/6	72/7	63/6	69/6
Istanbul	Poland	226/22	225/22	201/20	240/24	234/23	202/20	183/18	171/17	160/16	216/21	231/23	231/23
Istanbul	Ukrania	17/1	17/1	17/1	17/1	17/1	17/1	17/1	17/1	17/1	17/1	17/1	17/1
Istanbul	Russia	1/0	0/0	0/0	1/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0
Istanbul	Norway	11/1	11/1	13/1	12/1	13/1	12/1	12/1	11/1	11/1	12/1	13/1	12/1
Istanbul	Swedish	104/10	106/10	118/11	124/12	110/11	116/11	102/10	107/10	94/9	124/12	112/11	116/11
Istanbul	Switzerland	47/4	57/5	52/5	48/4	49/4	46/4	48/4	56/5	46/4	53/5	53/5	56/5
Istanbul	Holland	81/8	87/8	88/8	96/9	85/8	89/8	84/8	82/8	83/8	81/8	78/7	83/8
Istanbul	Denmark	8/0	8/0	5/0	7/0	6/0	7/0	5/0	6/0	6/0	60	11/1	8/0

Table 6.12 Mean values and standard deviations of the probabilistic export freight demands (in positions) of the order countries (Cont.)

Istanbul	Ireland	8/0	9/0	7/0	7/0	7/0	7/0	7/0	8/0	8/0	7/0	6/0	7/0
Istanbul	Luxembourg	2/0	2/0	2/0	2/0	2/0	1/0	2/0	2/0	0/0	4/0	4/0	1/0
Istanbul	Romania	59/5	53/5	46/4	49/4	39/3	59/5	48/4	43/4	13/1	21/2	44/4	59/5
Istanbul	Bulgaria	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0
Istanbul	Croatia	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Istanbul	Kosovo	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	0/0	1/0	1/0
Istanbul	Serbia	7/0	8/0	7/0	8/0	8/0	7/0	7/0	9/0	8/0	9/0	7/0	8/0
Izmir	Germany Region-1	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	3/0	4/0	4/0	4/0
Izmir	Germany Region-2	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Izmir	Germany Region-3	14/1	15/1	15/1	15/1	14/1	14/1	14/1	15/1	11/1	14/1	17/1	17/1
Izmir	Germany Region-4	21/2	25/2	20/2	20/2	19/1	19/1	20/2	19/1	18/1	20/2	30/3	26/2
Izmir	Germany Region-5	20/2	20/2	19/1	20/2	19/1	20/2	21/2	19/1	18/1	20/2	21/2	21/2
Izmir	Germany Region-6	17/1	18/1	17/1	19/1	18/1	19/1	19/1	18/1	17/1	19/1	20/2	22/2
Izmir	Germany Region-7	5/0	5/0	5/0	5/0	5/0	6/0	5/0	6/0	5/0	5/0	5/0	5/0
Izmir	Germany Region-8	7/0	9/0	9/0	9/0	9/0	9/0	9/0	9/0	8/0	9/0	9/0	9/0
Izmir	Germany Region-9	16/1	20/2	20/2	20/2	20/2	21/2	21/2	20/2	17/1	20/2	20/2	20/2
Izmir	Germany Region-10	5/0	5/0	2/0	3/0	2/0	3/0	2/0	2/0	2/0	3/0	7/0	6/0
Izmir	France Region-1	9/0	9/0	9/0	9/0	8/0	8/0	9/0	8/0	8/0	11/1	11/1	10/1
Izmir	France Region-2	33/3	30/3	25/2	29/2	29/2	28/2	33/3	28/2	29/2	38/3	38/3	37/3
Izmir	France Region-3	92/9	108/10	114/11	105/10	112/11	119/11	117/11	84/8	75/7	105/10	118/11	121/12
Izmir	France Region-4	32/3	31/3	31/3	33/3	31/3	31/3	37/3	32/3	27/2	39/3	39/3	38/3
Izmir	Portugal	3/0	4/0	4/0	4/0	3/0	3/0	4/0	3/0	3/0	4/0	4/0	4/0
Izmir	Spain	50/5	81/8	61/6	70/7	80/8	82/8	70/7	75/7	52/5	74/7	73/7	68/6
Izmir	England	54/5	43/4	45/4	48/4	53/5	51/5	52/5	55/5	47/5	51/5	56/5	57/5
Izmir	Belgium	18/1	22/2	22/2	20/2	21/2	21/2	24/2	21/2	19/1	19/1	19/1	21/2
Izmir	Austria	5/0	5/0	5/0	6/0	6/0	6/0	4/0	5/0	4/0	4/0	5/0	5/0
Izmir	Hungary	37/3	46/4	44/4	45/4	40/	43/4	44/4	37/3	33/3	39/3	44/4	44/4
Izmir	Italy	3/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	3/0	4/0	4/0	4/0
Izmir	Finland	2/0	2/0	1/0	2/0	2/0	2/0	2/0	2/0	1/0	2/0	1/0	2/0
Izmir	Slovakia	6/0	8/0	8/0	7/0	8/0	8/0	7/0	7/0	7/0	7/0	7/0	7/0
Izmir	Czech Republic	7/0	11/1	10/1	9/0	10/1	11/1	9/0	10/1	9/0	10/1	9/0	10/1
Izmir	Poland	6/0	6/0	5/0	6/0	6/0	5/0	5/0	4/0	4/0	5/0	6/0	6/0
Izmir	Norway	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0
Izmir	Swedish	21/2	22/2	24/2	26/2	23/2	24/2	21/2	22/2	19/1	26/2	23/2	24/2
Izmir	Switzerland	4/0	5/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0
Izmir	Holland	21/2	22/2	22/2	24/2	22/2	22/2	21/2	21/2	21/2	21/2	20/2	21/2

Table 6.12 Mean values and standard deviations of the probabilistic export freight demands (in positions) of the order countries (Cont.)

Izmir	Denmark	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	2/0	1/0
Izmir	Ireland	2/0	2/0	1/0	1/0	1/0	1/0	1/0	2/0	2/0	1/0	1/0	1/0
Mersin	Germany Region-2	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Mersin	Germany Region-4	2/0	3/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	3/0	3/0
Mersin	Germany Region-5	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	1/0	2/0	2/0	2/0
Mersin	Germany Region-7	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0
Mersin	Germany Region-8	12/1	15/1	15/1	15/1	15/1	15/1	15/1	15/1	14/1	15/1	15/1	15/1
Mersin	Germany Region-9	1/0	1/0	2/0	2/0	2/0	2/0	2/0	1/0	1/0	1/0	2/0	1/0
Mersin	France Region-1	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Mersin	France Region-4	4/0	4/0	4/0	4/0	4/0	4/0	5/0	4/0	3/0	5/0	5/0	5/0
Mersin	England	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0
Mersin	Belgium	3/0	4/0	4/0	3/0	3/0	3/0	4/0	3/0	3/0	3/0	3/0	3/0
Mersin	Hungary	7/0	9/0	9/0	9/0	8/0	9/0	9/0	7/0	7/0	8/0	9/0	9/0
Mersin	Italy	18/1	19/1	19/1	18/1	19/1	18/1	19/1	18/1	14/1	19/1	19/1	19/1
Mersin	Finland	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Mersin	Czech Republic	2/0	3/0	3/0	2/0	3/0	3/0	2/0	3/0	2/0	3/0	2/0	3/0
Mersin	Poland	6/0	6/0	6/0	7/0	7/0	6/0	5/0	5/0	5/0	6/0	7/0	7/0
Mersin	Swedish	1/0	1/0	2/0	2/0	2/0	2/0	1/0	1/0	1/0	2/0	2/0	2/0
Mersin	Holland	1/0	1/0	1/0	2/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0

Table 6.13 Mean values and standard deviations of the probabilistic import freight demands (in positions) of the order countries

Origin	Destination	December 2015	January 2016	February	March	April	May	June	July	August	September	October	November
Germany Region-1	Istanbul	10/1	12/1	8/0	11/1	10/1	12/1	11/1	13/1	9/0	13/1	11/1	12/1
Germany Region-1	Izmir	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Germany Region-2	Istanbul	9/0	9/0	9/0	10/1	10/1	9/0	10/1	10/1	9/0	9/0	9/0	9/0
Germany Region-2	Mersin	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Germany Region-3	Istanbul	49/4	54/5	51/5	54/5	50/5	50/5	52/5	53/5	42/4	54/5	57/5	55/5
Germany Region-3	Izmir	11/1	13/1	12/1	13/1	12/1	12/1	12/1	12/1	10/1	13/1	13/1	13/1
Germany Region-3	Mersin	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	2/0	3/0	3/0	3/0
Germany Region-4	Istanbul	250/25	234/23	293/29	308/30	294/29	295/29	307/30	310/31	292/29	315/31	312/31	298/29
Germany Region-4	Izmir	7/0	6/0	8/0	8/0	8/0	8/0	8/0	8/0	8/0	8/0	8/0	8/0
Germany Region-4	Mersin	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0
Germany Region-5	Istanbul	57/5	61/6	46/4	57/5	52/5	54/5	58/5	55/5	43/4	62/6	53/5	52/5
Germany Region-5	Izmir	8/0	8/0	6/0	8/0	7/0	7/0	8/0	7/0	6/0	8/0	7/0	7/0
Germany Region-5	Mersin	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0
Germany Region-6	Istanbul	86/8	86/8	90/9	88/8	88/8	88/8	91/9	95/9	90/9	97/9	99/9	90/9
Germany Region-6	Izmir	11/1	11/1	12/1	12/1	12/1	12/1	12/1	13/1	12/1	13/1	13/1	12/1
Germany Region-6	Mersin	7/0	7/0	7/0	7/0	7/0	7/0	7/0	7/0	7/0	7/0	8/0	7/0
Germany Region-7	Istanbul	223/22	167/16	232/23	246/24	249/24	246/24	252/25	246/24	240/24	249/24	251/25	245/24
Germany Region-7	Izmir	9/0	6/0	9/0	9/0	10/1	9/0	10/1	9/0	9/0	10/1	10/1	9/0
Germany Region-7	Mersin	11/1	8/0	12/1	12/1	12/1	12/1	13/1	12/1	12/1	12/1	13/1	12/1
Germany Region-8	Istanbul	396/39	257/25	413/41	464/46	462/46	460/4	465/46	466/46	463/46	466/46	462/46	460/46
Germany Region-8	Izmir	11/1	7/0	11/1	12/1	12/1	12/1	13/1	13/1	12/1	13/1	12/1	12/1
Germany Region-8	Mersin	19/1	12/1	19/1	22/2	22/2	22/2	22/2	22/2	22/2	22/2	22/2	22/2
Germany Region-9	Istanbul	67/6	60/6	67/6	75/7	76/7	78/7	82/8	88/8	73/7	85/8	83/8	77/7
Germany Region-9	Izmir	6/0	6/0	6/0	7/0	7/0	7/0	8/0	8/0	7/0	8/0	8/0	7/0
Germany Region-9	Mersin	5/0	4/0	5/0	5/0	5/0	6/0	6/0	6/0	5/0	6/0	6/0	5/0
Germany Region-10	Istanbul	36/3	28/2	36/3	40/4	40/4	41/4	41/4	40/4	39/3	41/4	40/4	40/4
Germany Region-10	Mersin	3/0	2/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0
France Region-1	Istanbul	14/1	14/1	14/1	15/1	15/1	15/1	14/1	14/1	11/1	14/1	16/1	16/1
France Region-1	Izmir	23/2	23/2	24/2	26/2	25/2	26/2	24/2	23/2	18/1	24/2	27/2	26/2
France Region-2	Istanbul	41/4	40/4	44/4	47/4	46/4	46/4	45/4	41/4	35/3	44/4	47/4	46/4
France Region-2	Izmir	58/5	57/5	61/6	65/	65/6	65/6	63/6	57/5	49/4	61/6	66/6	64/6
France Region-3	Istanbul	110/11	112/11	116/11	128/12	125/12	125/12	130/13	104/10	100/10	118/11	125/12	117/11
France Region-3	Izmir	76/7	78/7	81/8	89/8	87/8	87/8	91/9	72/7	70/7	82/8	87/8	82/8
France Region-4	Istanbul	36/3	36/3	37/3	41/4	39/3	39/3	39/3	36/3	31/3	38/3	41/4	50/5

Table 6.13 Mean values and standard deviations of the probabilistic import freight demands (in positions) of the order countries (Cont.)

France Region-4	Izmir	24/2	23/2	24/2	27/2	26/2	26/2	26/2	24/2	21/2	25/2	27/2	33/3
France Region-4	Mersin	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0
Greece	Istanbul	16/1	20/2	18/1	17/1	17/1	15/1	17/1	16/1	14/1	13/1	18/1	17/1
Portugal	Istanbul	4/0	4/0	4/0	5/0	4/0	4/0	5/0	4/0	4/0	4/0	4/0	4/0
Portugal	Izmir	9/0	9/0	9/0	11/1	9/0	8/0	11/1	9/0	8/0	8/0	9/0	8/0
Spain	Istanbul	58/5	59/5	62/6	63/6	62/6	64/6	61/6	58/5	56/5	56/5	58/5	63/6
Spain	Izmir	97/9	99/9	105/10	105/10	104/10	107/10	103/10	97/9	95/9	94/9	98/9	106/10
England	Istanbul	90/9	100/10	108/10	133/13	102/10	106/10	101/10	87/8	107/10	100/10	87/8	82/8
England	Izmir	7/0	8/0	8/0	10/1	8/0	8/0	8/0	7/0	8/0	8/0	7/0	6/0
Belgium	Istanbul	251/25	253/25	253/25	264/26	238/23	225/22	255/25	257/25	218/21	261/26	280/28	249/24
Belgium	Izmir	22/2	22/2	22/2	23/2	21/2	20/2	22/2	22/2	19/1	23/2	24/2	22/2
Slovenia	Istanbul	5/0	5/0	5/0	8/0	3/0	7/0	8/0	4/0	4/0	5/0	4/0	3/0
Austria	Istanbul	25/2	303	25/2	37/3	24/2	31/3	25/2	28/2	21/2	25/2	28/2	25/2
Hungary	Istanbul	86/8	118/11	122/12	136/13	114/11	121/12	137/13	120/12	94/9	130/13	129/12	123/12
Hungary	Izmir	9/0	12/1	13/1	14/1	12/1	12/1	14/1	12/1	10/1	13/1	13/1	13/1
Italy	Istanbul	197/19	207/20	211/21	220/22	220/22	227/22	229/22	206/20	178/17	204/20	216/21	230/23
Italy	Izmir	22/2	23/2	24/2	25/2	25/2	26/2	26/2	23/2	20/2	23/2	24/2	26/2
Italy	Mersin	8/0	9/0	9/0	9/0	9/0	10/1	10/1	9/0	8/0	9/0	9/0	10/1
Estonia	Istanbul	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2/0	0/0
Finland	Istanbul	14/1	12/1	13/1	13/1	13/1	13/1	13/1	13/1	13/1	12/1	13/1	14/1
Slovakia	Istanbul	26/2	32/3	28/2	29/2	31/3	29/2	28/2	32/3	28/2	29/2	30/3	30/3
Slovakia	Izmir	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0
Czech Republic	Istanbul	60/6	62/6	62/6	65/6	70/7	70/7	71/7	67/6	61/6	68/6	72/7	68/6
Czech Republic	Izmir	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0
Czech Republic	Mersin	2/0	2/0	2/0	2/0	3/0	3/0	3/0	2/0	2/0	2/0	3/0	2/0
Poland	Istanbul	322/32	319/31	313/31	333/33	331/33	331/33	330/33	327/32	181/18	328/32	303/30	301/30
Poland	Mersin	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	2/0	3/0	3/0	3/0
Ukrania	Istanbul	14/1	11/1	11/1	12/1	111	11/1	11/1	11/1	11/1	11/1	15/1	14/1
Russia	Istanbul	23/2	22/2	23/2	22/2	23/0	22/2	23/2	22/2	23/2	22/2	23/2	22/2
Norway	Istanbul	2/0	2/0	2/0	2/0	2/0	2/0	1/0	1/0	1/0	2/0	2/0	2/0
Norway	Izmir	1/0	1/0	1/0	1/0	1/0	1/0	1/0	0/0	0/0	1/0	1/0	1/0
Swedish	Istanbul	52/5	51/5	56/5	56/5	64/6	61/6	61/6	57/5	52/5	53/5	55/5	57/5
Swedish	Izmir	2/0	2/0	3/0	3/0	3/0	3/0	3/0	3/0	2/0	2/0	3/0	3/0
Switzerland	Istanbul	18/1	19/1	20/2	20/2	20/2	21/2	22/2	20/2	19/1	21/2	20/2	20/2
Switzerland	Izmir	4/0	4/0	5/0	5/0	5/0	5/0	5/0	4/0	4/0	5/0	5/0	5/0
Holland	Istanbul	143/14	106/10	103/10	106/10	107/10	106/10	108/10	104/10	95/9	109/10	148/14	143/14

Table 6.13 Mean values and standard deviations of the probabilistic import freight demands (in positions) of the order countries (Cont.)

Holland	Izmir	18/1	13/1	13/1	13/1	13/1	13/1	13/1	13/1	12/1	13/1	18/1	18/1
Holland	Mersin	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	3/0	2/0
Denmark	Istanbul	8/0	9/0	8/0	8/0	9/0	10/1	10/1	8/0	10/1	9/0	8/0	11/1
Denmark	Izmir	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0
Ireland	Istanbul	4/0	5/0	5/0	5/0	5/0	4/0	4/0	5/0	5/0	5/0	5/0	6/0
Luxembourg	Istanbul	0/0	1/0	0/0	1/0	0/0	1/0	0/0	1/0	0/0	1/0	0/0	1/0
Romania	Istanbul	52/5	49/4	52/5	60/6	58/5	58/5	60/6	45/4	13/1	18/1	55/5	43/4
Bulgaria	Istanbul	2/0	3/0	2/0	3/0	2/0	5/0	2/0	3/0	2/0	3/0	2/0	3/0
Serbia	Istanbul	2/0	2/0	2/0	2/0	2/0	2/0	2/0	3/0	2/0	6/0	2/0	6/0

6.5.2 Deterministic Optimization Results of Intermodal Fleet Planning

While generating the deterministic optimization results of the proposed holistic intermodal fleet planning models, most likely values of the triangular fuzzy numbers and the mean values of the stochastic freight demands are utilized. The deterministic multi-model load planning model is first solved with formerly given data through the optimization software LINGO 15.0 on an Intel Core i7 2 GHz IBM PC for each objective function separately. Then, the second, third and fourth model development phases of the proposed intermodal fleet management framework are added sequentially. Optimization details of these four different deterministic fleet planning models are presented in Table 6.14. It is obvious that total number of variables and constraints are increased dramatically when the components of fleet sizing and allocation are incorporated within the proposed model. It is also clear that external empty truck/trailer repositioning can be seen as the other important issue which causes increases in decision variables, model constraints and non-zero elements. When the scope of the proposed fleet planning model is extended by adding the different model development phases, the number of solver iterations, computational run time and optimality gap will also grow in the solution phase. If the fleet sizing, allocation and internal empty flows are incorporated into the intermodal freight transportation planning module, the overall transport cost will increase approximately 16% percent of its current value since the addition of fixed ownership costs and internal empty repositioning costs of trucks/trailers. Fortunately, the second phase decisions do not affect the total transit time and CO₂ emission objectives. However, the total transport cost, transit time and CO₂ emission objectives will deteriorate up to nearly 21%, 6% and 20% percent of their present values in case of truck/trailer inventories on the logistics network are included. Furthermore, integration of fleet expansion and reduction decisions can provide approximately 3.5%, 2.1% and 6.9% improvements on the total cost, transit time and environmental goals, respectively. Lastly, inclusion of external empty truck/trailer repositions can yield significant decreases in total transport cost objective since decreases in outsourcing quantities. In other words, it is possible to obtain cost reductions up to the 10.5% percent of its current value when the external empty flows are involved. On the other hand, these external empty flows do not have a considerable effect on the total transit time and CO₂ emission objectives.

Table 6.14 Optimization details of the deterministic fleet planning models in intermodal transportation networks

	Model-I: Multi-Mode Load Planning	Model-II: Fleet Sizing & Allocation with Internal Empty Flows	Model-III (a): Truck & Trailer Inventories	Model-III (b): Integrating Fleet Expansion & Reduction Decisions	Model IV: Holistic Intermodal Fleet Planning Model with External Empty Flows
Model class	MILP	MILP	MILP	MILP	MILP
Total number of variables	35765	140433	144418	144707	365062
Number of integer variables	35592	54408	54408	54408	54408
Total number of constraints	10762	144254	148275	148276	292253
Total non-zero elements	315808	958512	1160480	1160936	1824764
Total Transport Cost Objective					
Total number of iterations	179293	22824.42	39755254	67185260	22596600
CPU time (sec.)	16.97	97814	89209.55	85855.23	70842.29
Optimality gap (%)	0.0	0.01	0.007	0.011	0.011
Objective bound (€)	151890560,45	177030600	212691700	205119400	185510600
Best objective found (€)	151890560,45	177048670.2	212706551.6	205142320.54	185531432.5
Total Transit Time Objective					
Total number of iterations	2686	20429	48003520	19954807	8368047
CPU time (sec.)	6.50	47.16	89071.34	71062.22	70580.02
Optimality gap (%)	0.0	0.0	0.004	0.0012	0.0011
Objective bound (hrs.)	8558320	8558320	9073799	8884248	8846486
Best objective found (hrs.)	8558320	8558320	9074188.93	8884354.78	8846592
Total CO₂ Emission Objective					
Total number of iterations	1355	21747	41791357	60265241	19177118
CPU time (sec.)	6.54	47.39	87943.84	70988.19	70413.64
Optimality gap (%)	0.0	0.0	0.007	0.0022	0.003
Objective bound (kg)	98852810,63	98852857,51	118615500	110964700	108587200
Best objective found (kg)	98852810,63	98852780	118623880.7	110967141.4	108590800

6.5.3 Stochastic Optimization Results of Intermodal Fleet Planning

After presenting the deterministic optimization results of the proposed intermodal fleet planning models under crisp environments, the details of stochastic optimization model with probabilistic freight demands are given in Table 6.15. In other words, various stochastic optimization results are presented for each goal in accordance with the different values of sample or scenario size and probability associated with the chance constraints. In detail, several deterministic equivalent models are generated by altering the sample size and the pre-specified probability values. Note that the number of decision variables, constraints and non-zero elements of the deterministic equivalent forms will grow as the sample size is increased. On the other hand, a large sample size is appropriate for reducing the sampling error. However, computational effort will also increase (longer runtimes) in case of higher sample sizes. As it is clearly seen from Table 6.15 that all of the total cost, transit time and CO₂ emission objectives will become worse when the scenario size is increased. Moreover, these objective values will also increase rapidly if a relatively high probability is assigned to the chance constraint programming sets. It should be emphasized here that the number of unsatisfied scenarios for the import/export freight demand satisfactions will increase when a lower level of probability is specified. Actually, these unsatisfied scenarios report on the number of scenarios where the chance constraint programming set is violated (LINDO systems Inc., 2015). The number of the unsatisfied scenarios is the same for the probabilistic import and export freight demand satisfaction constraints. Because, the entire chance constraint set is determined as unsatisfied if just a single constraint is unsatisfied for a specific scenario. Furthermore, apart from the target probabilities of the chance constraint programming sets, the actual probabilities which correspond to the observed probability that a constraint set was satisfied in a particular scenario are also involved in this table. The actual probability of a stochastic program will be equal to 1.0 when there are no unsatisfied scenarios available. For instance, when the sample size is set to 20 and target probability is specified as 80% under cost orientation, the probabilistic demand satisfaction constraints are unsatisfied in a total of 4 out of 20 scenarios for an actual probability of 80% which exactly matches the target probability. Finally, when compared to the deterministic case, both truck and trailer fleet size requirements will increase under stochasticity of the freight demands.

Table 6.15 Optimization details of the proposed holistic intermodal fleet planning model under stochastic freight demands

Holistic Intermodal Fleet Planning Model under Stochastic Freight Demands									
P, Specified probability	Deterministic Equivalent Models								
N, Sample or scenario size	(N=5, P=0.5)	(N=5, P=0.7)	(N=5, P=0.8)	(N=10, P=0.5)	(N=10, P=0.7)	(N=10, P=0.9)	(N=20, P=0.75)	(N=20, P=0.8)	(N=20, P=0.9)
Model class	Chance-Constrained MILP								
Total random variables					3528				
Total number of variables		365072			365082			365102	
Number of integer variables		54418			54428			54448	
Total number of constraints		306367			324007			359287	
Total non-zero elements		1983534			2177584			2565684	
Total Transport Cost Objective									
Total number of iterations	50244207	1159333	1508949	13802158	4781597	1319746	19796490	6577695	1319739
CPU time (sec.)	86992.82	7236.91	8054.79	322262.24	21761.99	8605.6	268322.75	39312.89	7948.62
Unsatisfied scenarios (import)	2	0.0	0.0	5	3	0.0	5	4	2
Actual probability (import)	0.6	1.0	1.0	0.5	0.7	1.0	0.75	0.8	0.9
Unsatisfied scenarios (export)	2	0.0	0.0	5	3	0.0	5	4	2
Actual probability (export)	0.6	1.0	1.0	0.5	0.7	1.0	0.75	0.8	0.9
Optimality gap (%)	0.025	0.0	0.0	2.16	0.0	0.0	1.04	0.0	0.0
Objective bound (€)	203834700	210710664.54	210716566.23	202640300	210732953.8	215718945.9	215041000	217764142.3	219536999.9
Best objective found (€)	203886950.6	210710664.54	210716566.23	207025721.05	210732953.8	215718945.9	217294531.74	217764142.3	219536999.9
Total Transit Time Objective									
Total number of iterations	65249044	1387213	941515	37359367	15462120	1437757	5465488	9719562	7057697
CPU time (sec.)	67388.94	7722.11	6681.77	80581.53	64434.96	11405.09	11526.45	41754.62	40036.81
Unsatisfied scenarios (import)	2	0.0	0.0	5	3	0.0	5	4	2
Actual probability (import)	0.6	1.0	1.0	0.5	0.7	1.0	0.75	0.8	0.9
Unsatisfied scenarios (export)	2	0.0	0.0	5	3	0.0	5	4	2
Actual probability (export)	0.6	1.0	1.0	0.5	0.7	1.0	0.75	0.8	0.9
Optimality gap (%)	0.0	0.0	0.0	0.557	0.0	0.0	1.004	0.283	0.0
Objective bound (€)	9755485.22	10094392.62	10094404.57	9834056	10104848.19	10340555.83	10324550	10418440	10533980.34
Best objective found (€)	9755485.22	10094392.62	10094404.57	9888852.28	10104848.19	10340555.83	10428227.66	10447996.85	10533980.34
Total CO₂ Emission Objective									
Total number of iterations	51598508	1126504	35402208	31462815	19784354	4143488	21425052	25571882	21880821
CPU time (sec.)	88274.91	5505.68	63813.88	88252.56	69837.29	29324.28	88242.54	116268.01	69538.58
Unsatisfied scenarios (import)	2	0.0	0.0	5	3	0.0	5	4	2
Actual probability (import)	0.6	1.0	1.0	0.5	0.7	1.0	0.75	0.8	0.9
Unsatisfied scenarios (export)	2	0.0	0.0	5	3	0.0	5	4	2
Actual probability (export)	0.6	1.0	1.0	0.5	0.7	1.0	0.75	0.8	0.9
Optimality gap (%)	0.00188	0.0	0.0011	0.762	0.0	0.0	0.59	0.084	0.0016
Objective bound (€)	120004900	124622340.71	124620800	120883300	124636635.65	127917443.11	127837800	129080000	130399200
Best objective found (€)	120007166.11	124622340.71	124622131.95	121805323.38	124636635.65	127917443.11	128595067.3	129189126.09	130401367.8

6.5.4 Fuzzy Optimization Results of Intermodal Fleet Planning

This section presents optimization details of the proposed fuzzy intermodal fleet planning model with deterministic freight demands. In Table 6.16, fuzzy optimization results or α -acceptable fuzzy efficient solutions are given for each goal by considering various levels of feasibility degrees of constraints. The possibility distributions which present the ranges of the aspiration levels associated with the fuzzy goals are also included by table. There is no substantial increases in the number of decision variables, constraints and computational time after fuzzy to crisp transformation process. The computational results have displayed that the bigger the feasibility degree is, the worst the objective function value will be. In other words, when the maximum satisfaction degree of the objectives are achieved, the fulfilment levels of the fuzzy constraints may become comparatively lower. When only the uncertainty of the freight demands is taken into account, the deviation of total transport cost objective will varied in the range from 9.8% to 18.3%. Similarly, there will be increases in terms of the total transit time objective in the range of 10.2% and 19%. Finally, total CO₂ emission objective may be ranged between 10.5% and 20% of its former value in the deterministic case. On the other hand, when the stochasticity of the freight demands is ignored and just the fuzziness of the aforementioned model parameters is considered, the variations in these objective function values will not be in any appreciably degree. As a matter of fact the expected values of the total transport cost will even decrease if the feasibility degree is set to zero by a risk seeker. In detail, it is possible to provide cost reductions in fuzzy environment, i.e., approximately 1.2% of its present value in the deterministic case, in case of risk-seeking. On the other hand, when the feasibility degree of constraints is set to 1.0, total transport cost objective will increase nearly 1.9% of its current value due to risk-aversion. Fortunately, one can achieve lower transit times for all of the feasibility degrees of constraints under fuzzy environments. In this situation, it is able to decrease the total transit time objective down to 0.4% percent of its present value. However, environmental impact values under fuzzy environments will always be higher than the deterministic case for all of the feasibility degrees of constraints. Actually, total CO₂ emission value may increase up to 3.8% of its current value under fuzziness. It can be concluded that randomness of the freight demands is more effectual than the fuzziness of some model parameters on all of the fleet planning objectives.

Table 6.16 Optimization details of the proposed holistic intermodal fleet planning model under fuzzy environments

Holistic Intermodal Fleet Planning Model under Fuzzy Environments						
α -acceptable optimal solutions						
Model Class	MILP					
Total number of variables	368365					
Total number of integer variables	54408					
Total number of constraints	292418					
Total number of non-zero elements	4082943					
Feasibility degree, α	Objectives	Best Found Expected Value of the Objectives	Possibility Distribution of the Objectives	Total number of iterations	CPU time (sec.)	Optimality gap (%)
0.0	Total transport cost	183636316.27	(170007557.1, 184087895.26, 195729887.5)	83665722	72333.7	0.027
	Total transit time	8802674.7	(8005056.3, 8840865.02, 953711.59)	3845616	10309.29	0.0
	Total CO ₂ emission	111240931.54	(89025605.5, 108151880.84, 139817681.83)	100152301	67379.63	0.0035
0.2	Total transport cost	184437860.18	(170643774.8, 184848891.8, 196738766.07)	69148365	70973.13	0.025
	Total transit time	8806052.63	(8007437.45, 8844430.17, 9541750.86)	982713	2851.6	0.0
	Total CO ₂ emission	111534619.72	(89291853.5, 108450770.33, 140138654.91)	18082521	66782.69	0.0038
0.4	Total transport cost	185445011.72	(171457629.3, 185877428.7, 197859407.72)	14824660	14738.27	0.092
	Total transit time	8808689.47	(8008703.68, 8847140.48, 9545769.82)	752475	2863.57	0.0
	Total CO ₂ emission	111727966.24	(89471347.1, 108646982.59, 140346342.69)	57994730	66500.38	0.003
0.6	Total transport cost	186475082.48	(172217278.3, 186893508.8, 199115365.09)	4528364	14985.89	0.066
	Total transit time	8812819.78	(8010148.06, 8851382.68, 9552650.6)	1011967	13498.7	0.00147
	Total CO ₂ emission	111998715.05	(89698829.1, 108928282.21, 140655331.16)	28047733	66318.74	0.0023
0.8	Total transport cost	187637148.5	(172933485.56, 188164180.74, 200423671.94)	44762369	79422.28	0.023
	Total transit time	8817037.11	(8012391.06, 8855517.59, 9559273.31)	2551654	13308.46	0.00118
	Total CO ₂ emission	112270087.98	(89936975.7, 109212711.92, 140946810.35)	92800164	64952.69	0.0013
1.0	Total transport cost	189162888.21	(174291813.28, 189499176.22, 202488291.53)	41790575	79281.42	0.009
	Total transit time	8825648.59	(8018331.4, 8864216.2, 9570588.91)	528862	6957.52	0.0
	Total CO ₂ emission	112734095.77	(90365571.3, 109686190.76, 141440403.47)	46553336	64403.07	0.0034

6.5.5 Fuzzy and Stochastic Optimization Results of Intermodal Fleet Planning

In the previous sections, the stochastic and fuzzy parameters are considered disjointedly and thus the optimization results are reported separately. In this section, different uncertainty types such as randomness and fuzziness embedded into the intermodal fleet planning problem are considered within a single optimization model. The computational results of the proposed multi-objective fuzzy and stochastic model are presented for each objective function as in Tables 6.17 and 6.18. In fact, these tables represent the fuzzy and crisp payoff matrices, respectively. The crisp payoff matrix incorporates the expected values of the fuzzy goals which are tried to be minimized by using LINGO 15.0 optimization suite. Actually, these are the direct optimization results whereas the fuzzy payoff matrix represents the indirect optimization outcomes. Because, the possibility distributions of these fuzzy goals are calculated within the optimization model by utilizing the pessimistic, most likely and optimistic values of the fuzzy objective function coefficients. Therefore, fuzzy payoff matrix may just present useful information about the ranges of the uncertain goals to the company experts. The following results which are obtained from the solution of fuzzy and stochastic fleet planning model can be used as benchmarks to construct the membership functions of these fuzzy goals. Indeed, the crisp payoff matrix consisting of the expected values of the fuzzy goals is used by the company experts to construct the membership functions while handling these conflicting objectives simultaneously. The computational experiments have shown that the number of decision variables, constraints and non-zero elements will increase quickly when compared to the deterministic and pure stochastic or fuzzy cases. It has been also displayed that overall transport cost, transit time and CO₂ emission values will increase when the random and fuzzy model parameters are taken into account in an integrated manner. Besides, when the number of sample size (N) for the probabilistic freight demands and the feasibility degree (α) of the fuzzy constraints are increased, all of the objective function values will increase due to the higher level of stochastic demand satisfaction and lower level of risk related to the violations in the fuzzy constraints. As mentioned previously, the effects of stochastic freight demands on the objective values are more apparent than the fuzzy parameters. The more reliable and risk-free fleet plans can be provided in case of larger the sample size, higher probability and feasibility degree.

Table 6.17 The corresponding fuzzy payoff matrix for the multi-objective fuzzy & stochastic fleet planning model under a 24-hour runtime limit ($N=5$, $P=90\%$)

Feasibility degree, α	Objectives	Total transport cost (€)	Total transit time (hr)	Total CO ₂ emission (kg)
0.0	Total transport cost	(193052782.1, 208777440.2 , 222171138.5)	(9724715.6, 10775025.6, 11705140.2)	(113642141.5, 138505310.9, 177485283.3)
	Total transit time	(1357195124.1, 1681164853.6, 1974968518.9)	(9119527.2, 10081546.1 , 10883616.1)	(111191503.4, 134513245, 171336896.8)
	Total CO ₂ emission	(1327341781.5, 1647685738.5, 1936054824)	(9754634.6, 10681874.7, 11442615.5)	(102145864.3, 123965762 , 160148626.9)
0.2	Total transport cost	(193745534.4, 209817614.1 , 223561050.7)	(9723969.9, 10775636.4, 11706182.8)	(113418710.6, 138287367.5, 177261507.4)
	Total transit time	(1561873225.8, 1946508061.4, 2292614077.5)	(9126618.6, 10092015.1 , 10898338.5)	(111617164.9, 134970945.5, 171763407.9)
	Total CO ₂ emission	(1172376328.8, 1442709358.3, 1691486787.4)	(9769351.2, 10700872.5, 11465927.3)	(102593382, 124456178.7 , 160658805.7)
0.4	Total transport cost	(194515664, 210918787.6 , 224539389.3)	(9712744.1, 10774507.4, 11715657)	(113374988.2, 138352228.8, 177390004.3)
	Total transit time	(1375235176.9, 1703915960.3, 2002796524.5)	(9130499, 10098213.6 , 10907583.1)	(111818001.5, 135147073.1, 171887537.7)
	Total CO ₂ emission	(1336452745.8, 1658523260.1, 1948542642.1)	(9774241.6, 10708148.2, 11476415.8)	(102851487.7, 124747712.7 , 160978378.7)
0.6	Total transport cost	(195501330.4, 212402488.3 , 226133845.6)	(9711658.3, 10782619, 11736390.9)	(113988421.1, 139146860.6, 178302754.8)
	Total transit time	(1512269018.9, 1883858613, 2218698561.7)	(9134519.1, 10106217.5 , 10920335.5)	(112199534.3, 135605486.4, 172374606.8)
	Total CO ₂ emission	(1172341040.7, 1443356525.5, 1692701117.5)	(9783813, 10721510.8, 11493297.7)	(103194369.5, 125132090.2 , 161364744.4)
0.8	Total transport cost	(196814327.8, 213737610.3 , 227937389.3)	(9715410.9, 10806310.2, 11785024.5)	(114773955.4, 140274455.6, 179679179.6)
	Total transit time	(1569798971.7, 1955247838.5, 2302698914)	(9138710.1, 10113262.1 , 10931011)	(112435880.9, 135878453.2, 172658198.3)
	Total CO ₂ emission	(1357344562.1, 1682416105.5, 1977314368.1)	(9795698.4, 10737338.5, 11513596.5)	(103467298.9, 125456526.2 , 161712467.8)
1.0	Total transport cost	(198292114.5, 215671215.9 , 230194031.4)	(9706217.8, 10809555.9, 11806162.7)	(115458312.3, 141202682.3, 180730190.6)
	Total transit time	(1509272104.4, 1880424440.1, 2214635378.6)	(9146078, 10128090 , 10955099.8)	(112912321.3, 136441933.4, 173249479.1)
	Total CO ₂ emission	(1184235779.2, 1457041168.7, 1708359455.5)	(9812867.4, 10761214.1, 11544826.7)	(103972024.5, 126040026 , 162329980.7)

Table 6.18 The corresponding crisp payoff matrix including expected values of the fuzzy goals under a 24-hour runtime limit ($N=5$, $P=90\%$)

Feasibility degree, α	Objectives	Total transport cost (€)	Total transit time (hr)	Total CO ₂ emission (kg)	Elapsed Runtime (sec.)	Number of iterations	Optimality gap (%)
0	Total transport cost	208368155.8	10736858.7	141836614.5	20188.68	3224705	0.0
	Total transit time	1674669842.01	10037396.5	137788578.2	2633.58	507807	0.0
	Total CO ₂ emission	1640759687.41	10637771.95	127504456.2	86400	67926733	0.00098
0.2	Total transport cost	209419589.7	10737214.4	141614404.03	17342.22	3393198	0.0
	Total transit time	1938021117.6	10048018.1	138228368.6	86400	24693484	0.00099
	Total CO ₂ emission	1438408811.8	10656699.5	127986123.9	86400	2600101	0.001
0.4	Total transport cost	210419679.4	10735874.6	141659287.9	21336.49	4279650	0.0
	Total transit time	1697548125.4	10054329.5	138394970.3	86400	9575045	0.000995
	Total CO ₂ emission	1651620834.03	10664107.4	128274162.2	86400	52341878	0.0021
0.6	Total transport cost	211822490.08	10744465.4	142426918.7	22034.72	4103784	0.0
	Total transit time	1875835216.8	10062419.4	138838314.02	86400	18632302	0.0065
	Total CO ₂ emission	1438980115.3	10677337.08	128645947.3	86400	6537921	0.0086
0.8	Total transport cost	213275778.8	10768660.5	143511196.8	25092.01	4363353	0.0
	Total transit time	1946961293.1	10069571.06	139102413.8	86400	15404999	0.0054
	Total CO ₂ emission	1676043936.04	10693201.5	128960638.2	86400	4049039	0.0177
1.0	Total transport cost	215180409.6	10772720.2	144393276.7	86400	11272108	0.011
	Total transit time	1872422461.8	10084612.1	139643963.1	86400	15809425	0.00962
	Total CO ₂ emission	1452701834.7	10717087.2	129527566.3	86400	15164830	0.02

6.5.6 Fuzzy Multi-Objective Optimization Results of the Proposed Fuzzy and Stochastic Intermodal Fleet Planning Model

After the single objective optimization results in the previous sub-sections, multi-objective optimization results of the final fuzzy-stochastic intermodal fleet planning model are presented in this section. A weighted additive fuzzy goal programming approach is employed since its simplicity and ease of use in order to solve the developed model with several conflicting objectives. Therefore, numerous compromise solutions can be offered to EKOL Logistics Inc. under different uncertainty levels. Detailed explanations related to the weighted additive fuzzy goal programming approach was formerly given in sub-section 5.4.2.3 of Chapter 5. In this section, it is assumed that aspiration levels of the objectives are fuzzy in nature because of the epistemic uncertainty, lack of information, incomplete data and the difficulty of certain data collection. The minimum and maximum limits on these objectives are estimated by making use of crisp payoff matrix given in Table 6.18 and thus guaranteed feasibility of each fuzzy goal in the solution phase. These limits are also used to construct the membership functions of the fuzzy goals for each feasibility degree of constraints. It should be noted here that maximum limits of the total transport cost objective are provided by the fully usage of outsourcing option in contrast to the transit time and environmental goals. In other words, upper bounds of the cost objective are not specified through the crisp payoff matrix. Because, this matrix contain relatively high cost values and may cause bias while generating the compromise solutions in multi-objective optimization. For this reason, it is preferred to utilize the cost values of fully outsourcing transportation alternative which is an undesirable condition for the logistics company. In order to quantify the fuzzy aspiration levels of the objectives, linear and continuous membership functions are found suitable. For instance, the membership functions of the fuzzy goals and regarding analytical definitions are shown in Figure 6.40 where the feasibility degree is equal to 0.4. As discussed in the previous Chapter 5, the objective weights are assigned as 0.425, 0.334 and 0.241 for the total transport cost, transit time and environmental goals, respectively. Actually, these relative importance weights are determined based on the desirable achievement degrees or overall priorities under a fuzzy group decision making environment. In summary, the proposed fuzzy multi-

objective intermodal fleet planning model can be converted into a single objective crisp equivalent form as in the following Equation (6.179) via weighted additive fuzzy goal programming. Indeed, the following weighted additive model is formulated for a specific feasibility degree ($\alpha = 0.4$):

$$\left\{ \begin{array}{l} \text{Maximize } 0.425 \times \mu_{\text{Cost}} + 0.334 \times \mu_{\text{Transit-time}} + 0.241 \times \mu_{\text{CO}_2} \\ \mu_{\text{Cost}} \leq \frac{278559021.3 - Z_{\text{Cost}}}{68139341.9} \\ \mu_{\text{Transit-time}} \leq \frac{10054329.5 - Z_{\text{Transit-time}}}{681545.1} \\ \mu_{\text{CO}_2} \leq \frac{141649278.9 - Z_{\text{CO}_2}}{13385116.7} \\ \sum_{k=1}^3 w_k = 0.425 + 0.334 + 0.241 = 1 \quad 0 \leq w_k \leq 1 \\ \text{Probabilistic, Fuzzy and Deterministic Constraint sets (6.33) – (6.147)} \\ 0 \leq \mu_{\text{Cost}}, \mu_{\text{Transit-time}}, \mu_{\text{CO}_2} \leq 1 \end{array} \right. \quad (6.179)$$

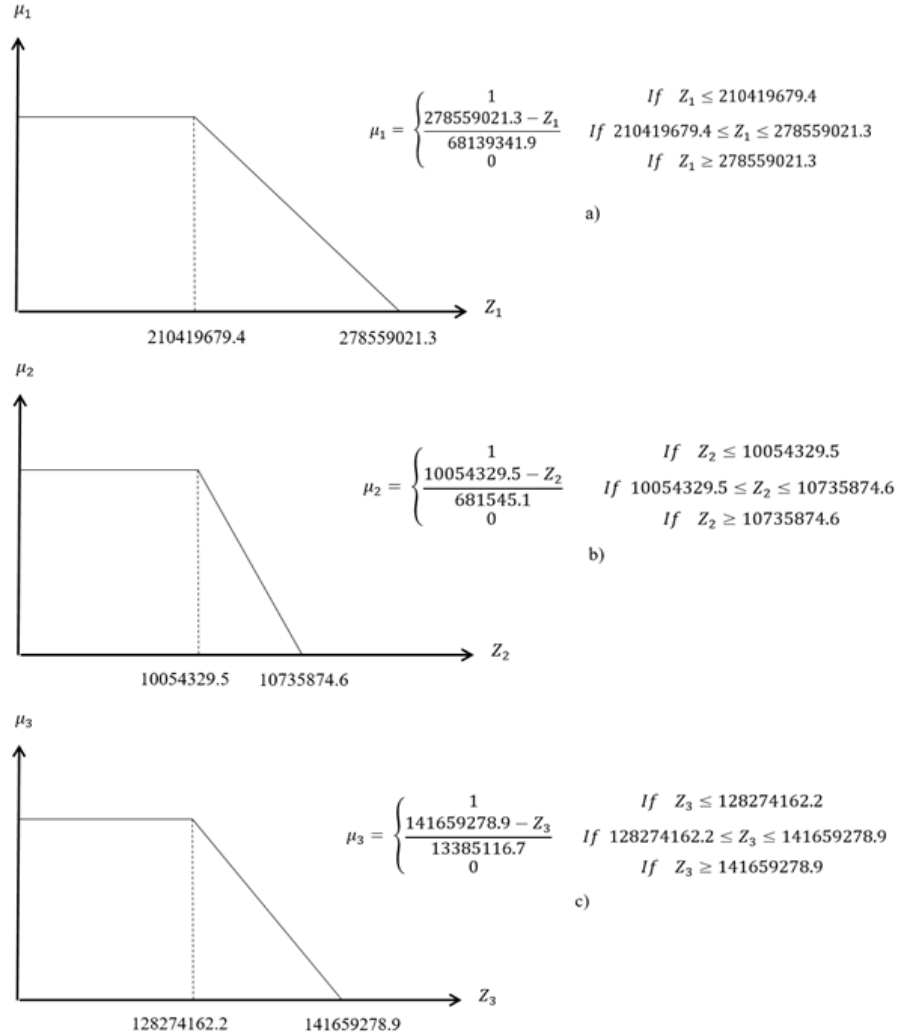


Figure 6.40 Membership functions of fuzzy goals and their analytical definitions when the feasibility degree is equal to 0.4: a) Total transport cost, b) Total transit time, c) Total CO₂ emission

After transforming the fuzzy multi-objective stochastic optimization model into the single-objective deterministic equivalent model, the following compromise solutions can be yielded as in Tables 6.19 and 6.20 for different feasibility degrees of constraints. Actually, these solutions are valid when the sample size is set to 5 and the relevant probabilities of the chance constraints are specified as 90%. In Table 6.19, objective values associated with the compromise solutions are provided. The regarding satisfaction degrees of the fuzzy goals are also given by Table 6.20.

Table 6.19 Fuzzy multi-objective optimization results under a 24-hour runtime limit ($N=5$, $P=90\%$)

Feasibility degree, α	Total transport cost (€)	Total transit time (hrs)	Total CO ₂ emission (kg)	Optimality gap (%)
0.0	223905622	10296311.8	136027055.7	1.38
0.2	224061184.9	10295298.8	136388944.2	0.0655
0.4	224879894.8	10293739.5	136822122.1	0.0653
0.6	225838131.7	10296600.4	137288642.1	0.074
0.75	225030213.7	10327314.8	137544296.1	0.186
1.0	227121521.1	10348781.8	138402596	1.51

Table 6.20 Provided results via weighted additive fuzzy goal programming approach ($N=5$, $P=90\%$)

Feasibility degree, α	Global Weighted Satisfaction Degree ($w_1 \cdot \mu_{z1} + w_2 \cdot \mu_{z2} + w_3 \cdot \mu_{z3}$)	Satisfaction Degree μ_{z1}	Satisfaction Degree μ_{z2}	Satisfaction Degree μ_{z3}
0.0	0.6389770	0.7786398	0.6298367	0.4053513
0.2	0.6415665	0.7882309	0.6412044	0.3834277
0.4	0.6385760	0.7877846	0.6487247	0.3613837
0.6	0.6449223	0.7899855	0.6566493	0.3728530
0.75	0.6581661	0.8199471	0.6313150	0.4100805
1.0	0.6478208	0.8115908	0.6160927	0.4029865

Among these above compromise solutions, a balance solution between the feasibility degree of constraints and global satisfaction degree should be found. Just because of this, company experts of EKOL Logistics Inc. are asked to specify aspiration levels of total transport cost, transit time, CO₂ emission values and their tolerance thresholds for the fuzzy & stochastic case. According to fuzzy payoff matrix given in Table 6.17, the general membership functions are constructed by EKOL Logistics Inc. as in Figure 6.41. In detail, it is assumed that the company experts will be fully satisfied with a cost objective value lower than €193052782.1 and they will be unsatisfied with a cost value of more than €278559021.3. Similarly, they will be fully satisfied with a total transit time value lower than 10037396.5 hours and a transit time value of more than 10772720.2 hours make the company experts unsatisfied. Furthermore, it is assumed that they will be fully satisfied with the environmental impact value lower than 127504456.2 kg and a total CO₂ emission value of more than

144393276.7 kg. make them unsatisfied again. Calculation of the compatibility index or global satisfaction degree of each α -parametric compromise solution with respect to aspirations of EKOL Logistics can be made as in the following Table 6.21.

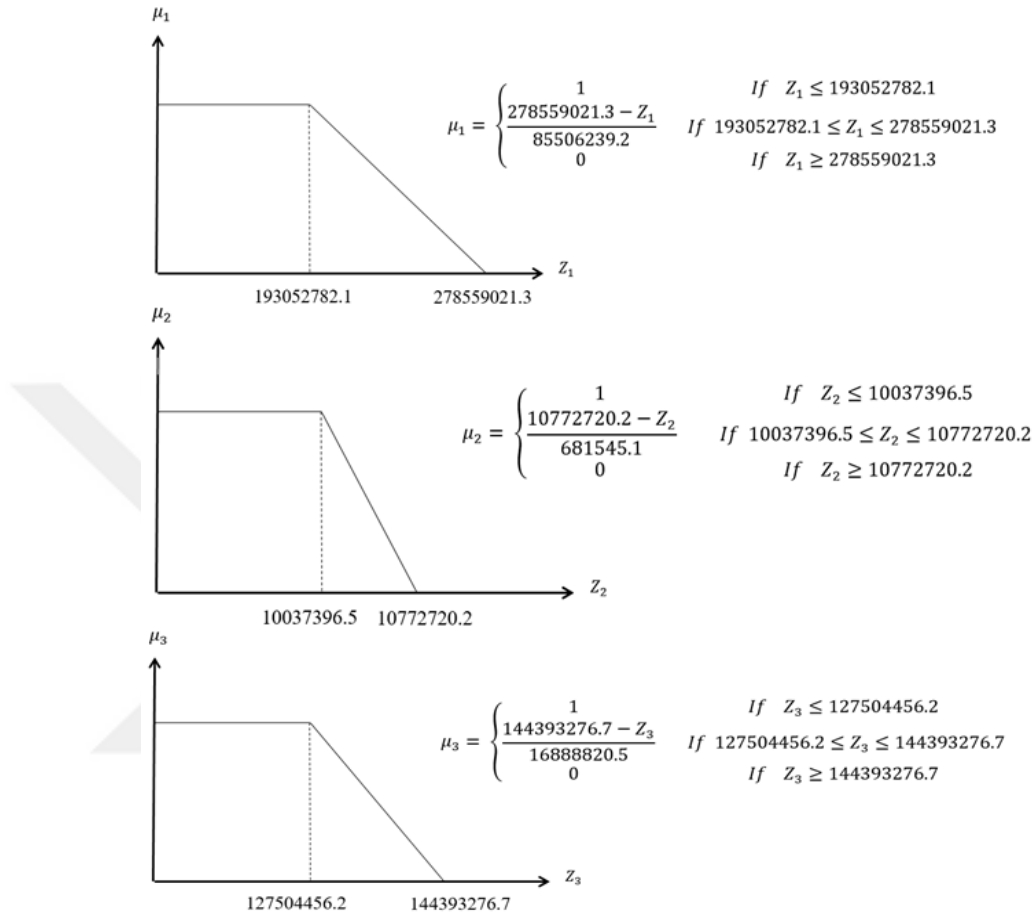


Figure 6.41 The general membership functions constructed by using the fuzzy payoff matrix

Since there is no known compromise solution at $\alpha = 0.8$ feasibility degree within the 24-hour runtime limit, results of $\alpha = 0.75$ is presented in Tables 6.19 to 6.21. According to fuzzy decision set, the best compromise choice would be the solution provided by solving the weighted additive model corresponding to $\alpha = 1.0$ in which the greatest membership degree is occurred.

Table 6.21 Calculation of the fuzzy decision for finding a balanced compromise solution ($N=5, P=90\%$)

Feasibility degree, α	Global Satisfaction Degree μ_{z1}	Global Satisfaction Degree μ_{z2}	Global Satisfaction Degree μ_{z3}	Fuzzy Decision
0.0	0.639	0.699	0.495	0.0
0.2	0.637	0.7	0.473	0.1206
0.4	0.627	0.702	0.448	0.2369
0.6	0.616	0.698	0.421	0.347
0.75	0.626	0.6535	0.4055	0.4212
1.0	0.601	0.622	0.354	0.5256

6.5.7 Numerical Results and Comparisons

In this section, numerical results of the provided compromise solution with $\alpha = 1.0$ feasibility degree are given and compared with the results of deterministic, stochastic and fuzzy and stochastic optimization cases. While visualization of the numerical results, four different model development phases of the proposed DSS are taken into account. In other words, the numerical results are presented with respect to the four different modules of the proposed mathematical programming based DSS.

6.5.7.1 Module I: Multi-Mode Load Planning or Freight Transportation Planning

The usage rates of different transportation modes and outsourcing are given in Figure 6.42 for the previously acquired compromise solution where feasibility degree, scenario size and probability is set to 1, 5 and 90%, respectively. In addition, the variation of the monthly transportation costs can be shown by Figure 6.43.

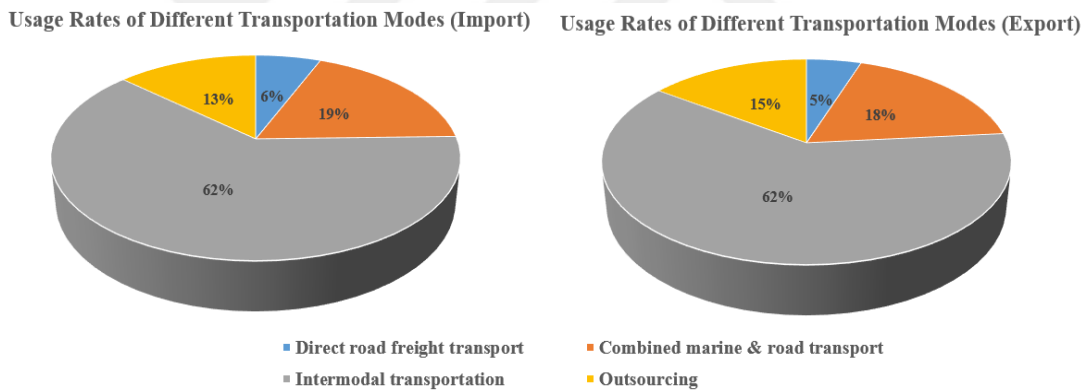


Figure 6.42 Usage rates of different transport modes in compromise solution ($\alpha = 1$, $N=5$ and $P=0.9$)

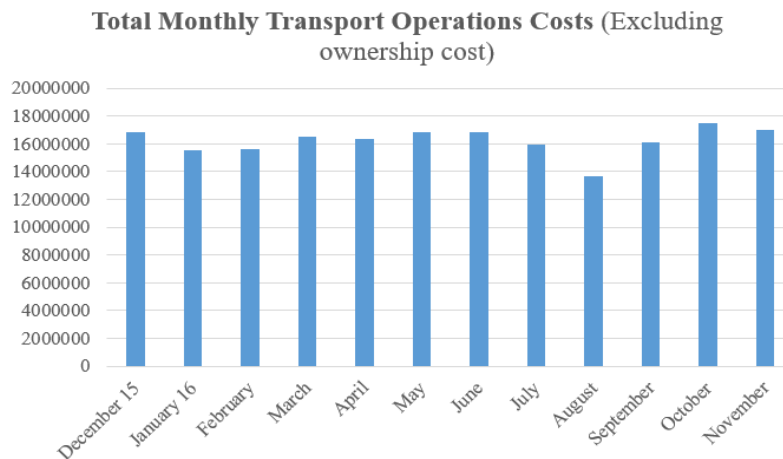


Figure 6.43 The variation of the monthly total transportation costs

It should be emphasized here that intermodal transportation is the most preferred option for the import/export transportation services. According to the following Figure 6.44 that marine and road freight transport costs constitute the large portion of the overall annual transport costs. The monthly variation associated with the usage rate of outsourcing option is also presented for both import and export transportation operations in Figure 6.45.

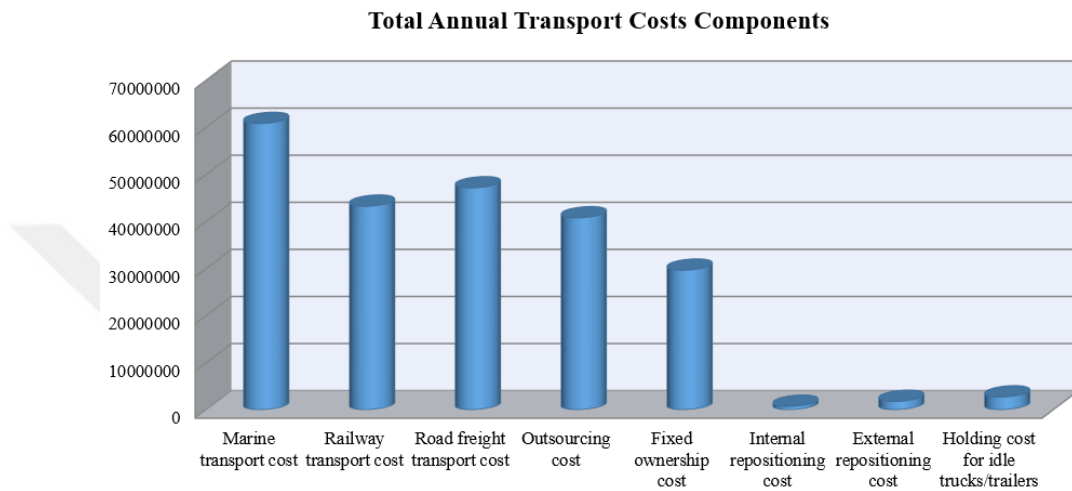


Figure 6.44 Comparison of the total transport cost's components

It is clearly seen from Figure 6.45 that the outsourcing quantity in freight exportation is relatively higher than the importation operations at the beginning of the planning horizon. On the other hand, the usage ratio of outsourcing for import operations will increase dramatically after a quarter of the year. Then, these outsourcing amounts may be almost the same for the import and export transportation services to the end of the planning period.

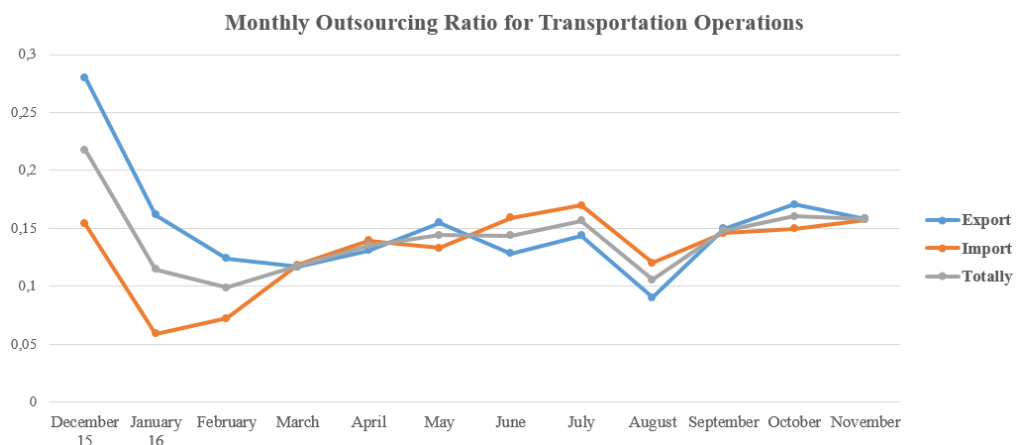


Figure 6.45 The monthly variation of the outsourcing ratio for import/export transportation operations

Similarly, the variations of the monthly transit times and CO₂ emission values are also presented in Figures 6.46 and 6.48, respectively. It should be noted here that there is a balance among the months in terms of the transport costs, transit times and environmental objectives. In other words, these objective values are not too unsteady throughout the planning period. Moreover, the components of the transit time objective are compared in the following Figure 6.47.

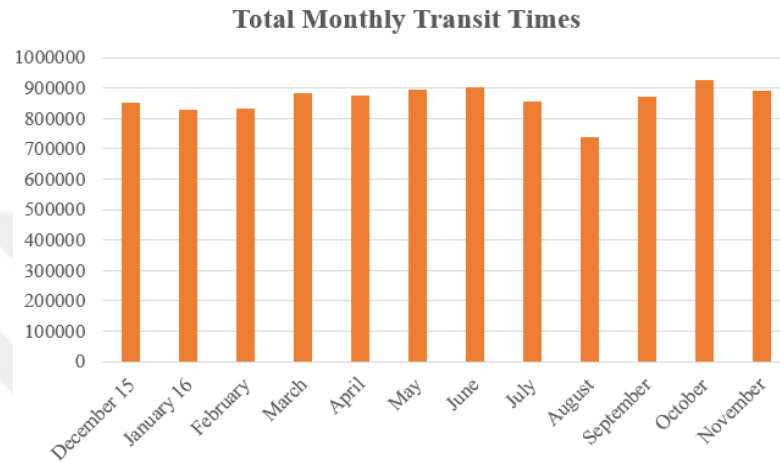


Figure 6.46 The variation of the monthly total transit times

It is obviously seen from Figure 6.47 that intermodal transportation has the largest transit times and can be seen as the most low speed transportation mode. The combined marine and road freight transportation and the outsourcing option are the other transportation alternatives which may cause significant increases in total transit times. The most important reason is that highly utilization of maritime logistics services within these transportation alternatives.

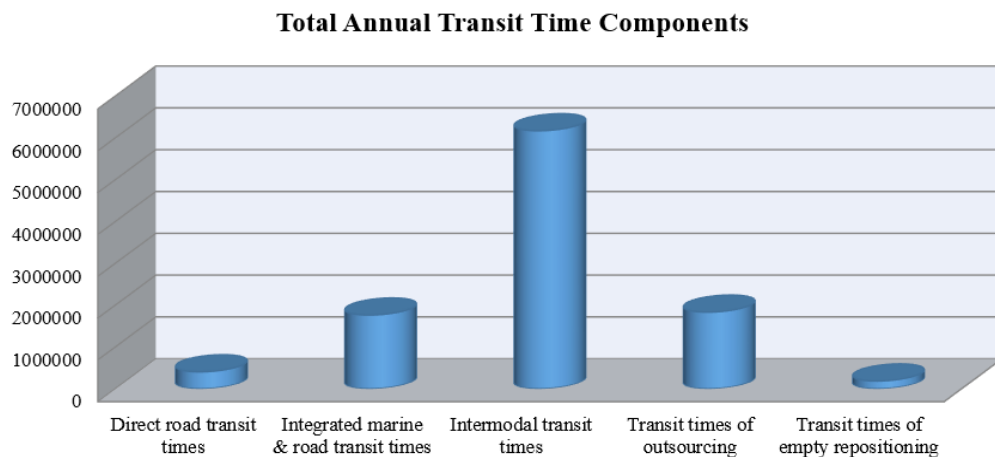


Figure 6.47 Comparison of the total annual transit time's components

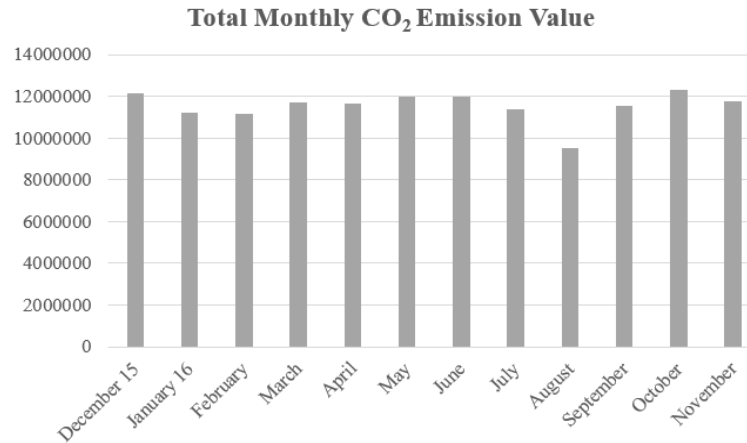


Figure 6.48 The variation of the monthly total environmental impact values

The effects of empty truck/trailer repositions on these objectives are also examined. It can be mentioned here that only minor increases may exist in total cost, transit time and environmental goals when the empty flows are included. The main components of the environmental goal which establish the total CO₂ emissions are also given by Figure 6.49. Computational experiments have shown that rail transport is the most environmentally friendly way of freight transportation. Furthermore, both of the internal and external empty truck/trailer repositioning do not too much increase the environmental pollution. However, direct road freight transport, marine transport and outsourcing services may have substantial influence on the total CO₂ emission objective. Because, as mentioned previously in Chapter 5, road and marine transports have the largest carbon dioxide, hydrocarbon, particle and nitrogen emission values in freight transportation. Finally, load planning results in marine and railway transports are presented in Tables 6.22 and 6.23, respectively.

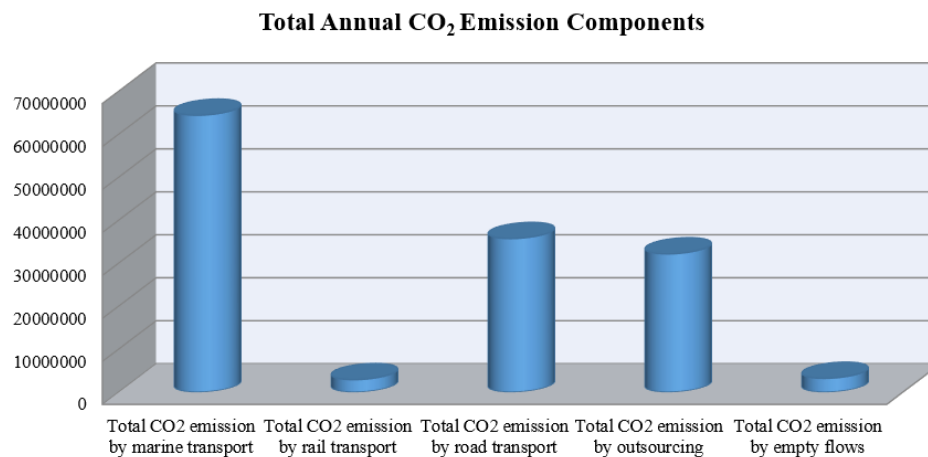


Figure 6.49 Comparison of the total environmental impact's components

Table 6.22 Load planning in maritime transportation

Months	Dec. 15	Jan. 16	Feb.	Mar.	Apr.	May	June	July	Augu.	Sep.	Oct.	Nov.
The import/export load quantities in marine transport by the company-owned Ro-Ro vessels												
Istanbul/Lavrion	0	41	134	45	41	70	43	45	51	47	41	44
Istanbul/Trieste	1922	2420	2455	2530	2574	2420	2707	2530	2284	2530	2530	2530
Izmir/Sete	239	265	269	255	267	264	270	230	179	260	282	314
Lavrion/Istanbul	0	67	133	45	41	39	19	18	46	15	19	18
Trieste/Istanbul	2017	2329	2430	2530	2530	2530	2530	2498	2363	2579	2530	2530
Sete/Izmir	286	284	315	324	291	299	277	262	222	281	326	318
The import/export load quantities in marine transport by the other logistics service providers' Ro-Ro vessels												
Istanbul/Trieste	0	53	0	148	0	195	0	21	0	75	202	195
Istanbul/Toulon	0	153	175	181	176	173	179	172	157	175	197	172
Izmir/Trieste	162	241	243	266	314	246	271	268	290	242	277	275
Mersin/Trieste	67	76	80	77	77	77	76	72	64	78	78	73
Trieste/Istanbul	0	0	0	198	38	85	133	0	0	0	130	52
Toulon/Istanbul	0	91	134	147	144	173	145	130	133	151	140	144
Trieste/Izmir	25	53	42	45	43	44	47	41	37	43	43	46
Trieste/Mersin	0	9	9	9	9	12	12	9	8	9	9	11

In fact, Table 6.22 gives the import/export load quantities in marine transportation by the company-owned Ro-Ro vessels and other logistics service providers' Ro-Ro vessels. According to this table, most of the freights should be transferred through the company-owned Ro-Ro vessels on the marine link between Istanbul and Trieste ports. Izmir – Trieste and Izmir – Sete are the other important marine links where the considerable amounts of freights are transferred. The number of chartered block trains and the load quantities transported by the public trains are also represented by Table 6.23. It is obvious that most of the freights are transferred by block trains from Trieste port to Cologne or Ludwigshafen stations. Furthermore, lots of loads are transported on the rail line between Trieste and Munich by the public trains. Instead of Malmö station, all of the freights are shipped to Gothenburg station from Cologne.

Table 6.23 Load planning in railway transportation

Months	Dec. 15	Jan. 16	Feb.	Mar.	Apr.	May	June	July	Augu.	Sep.	Oct.	Nov.
Number of trips for block train services												
Trieste/Ostrava	12	10	11	11	11	11	11	11	11	12	11	11
Trieste/Ludwig.	23	23	24	23	25	23	25	24	24	25	23	25
Trieste/Cologne	36	33	37	36	36	36	37	37	36	36	36	37
Ostrava/Trieste	12	10	11	11	11	11	10	11	11	12	11	11
Ludwig./Trieste	24	22	24	24	24	24	25	24	24	25	23	25
Cologne/Trieste	36	33	36	36	36	36	38	36	36	37	35	37
The import/export load quantities transferred by public trains												
Trieste/Munich	0	381	243	388	305	398	393	288	178	299	644	587
Cologne/Malmö	0	0	0	0	0	0	0	0	0	0	0	0
Cologne/Guthe.	63	71	118	96	111	100	89	128	156	129	163	176
Munich/Trieste	4	264	217	370	273	372	360	252	182	262	591	434
Malmö/Cologne	0	0	0	0	0	0	0	0	0	0	0	0
Guthe./Cologne	62	88	85	90	101	102	100	93	89	88	88	95



Figure 6.50 Comparison of the single and multi-objective load planning results under uncertainty

In Figure 6.50, the results of the deterministic, stochastic, fuzzy, fuzzy and stochastic and multi-objective optimization cases are compared to each other in terms of the multi-mode load planning issues. It is displayed that usage rate of intermodal transportation may increase when the stochasticity and fuzziness of some model parameters are taken into consideration. Opposite to the other single objective optimization cases, it is also revealed that amounts of loads which are shipped by direct road freight transport services will grow in case of fuzzy multi-objective optimization.

6.5.7.2 Module II: Truck/Trailer Fleet Size Optimization and Fleet Allocation

This module of the proposed DSS may also involve some important outcomes such as the loaded truck positions/movements, truck/trailer fleet sizing, fleet allocation and internal truck/trailer empty flows. Firstly, the loaded truck positions between the different locations, hubs and terminals are presented in Figures 6.51 to 6.54.

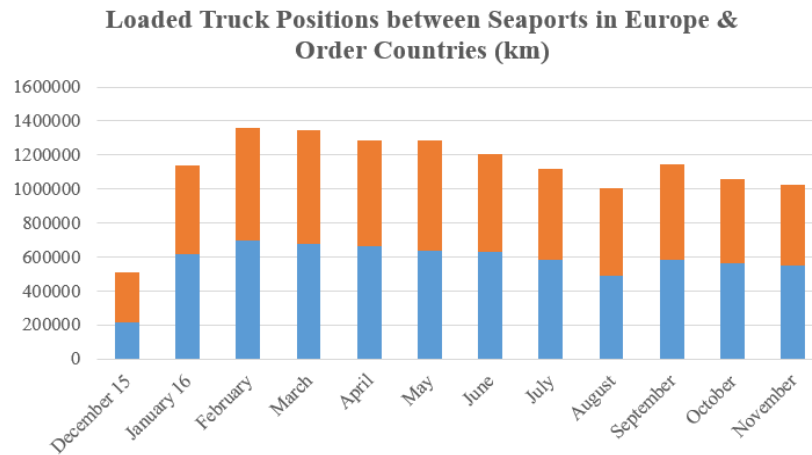


Figure 6.51 Amounts of loaded truck positions (in kilometer) by European plated trucks between seaports in Europe and order countries

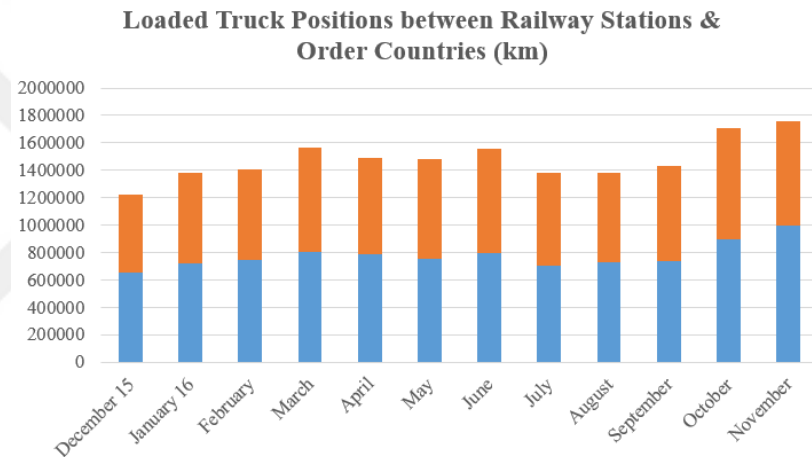


Figure 6.52 Amounts of loaded truck positions (in kilometer) by European plated trucks between railway stations and order countries

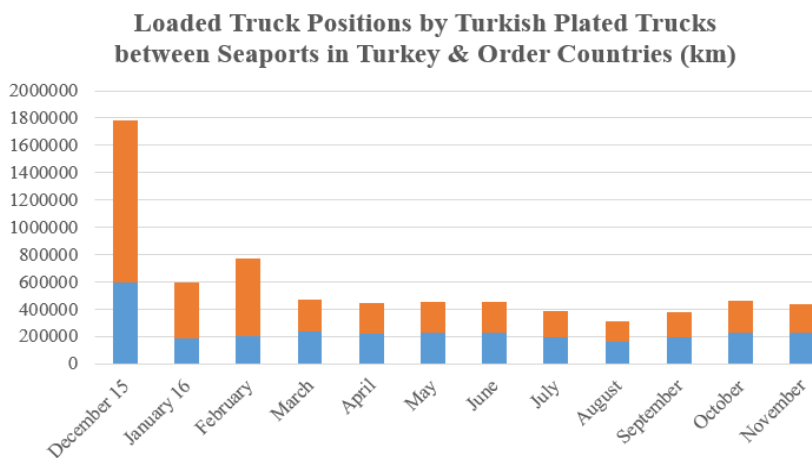


Figure 6.53 Amounts of loaded truck positions (in kilometer) by Turkish plated trucks between seaports in Turkey and order countries

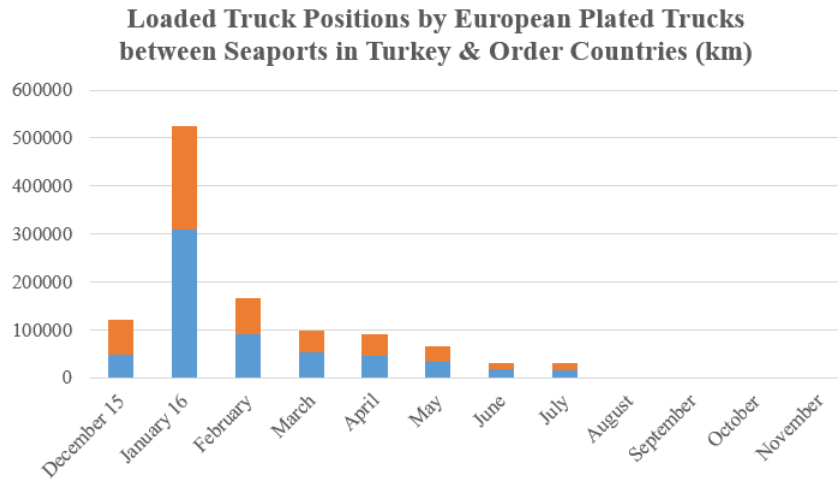


Figure 6.54 Amounts of loaded truck positions (in kilometer) by European plated trucks between seaports in Turkey and order countries

In detail, the quantities of loaded truck positions by European plated trucks between the seaports and railway stations in Europe and order countries are shown by Figures 6.51 and 6.52, respectively. Additionally, Figures 6.53 and 6.54 demonstrated the loaded truck movements between the seaports in Turkey and order countries via Turkish and European plated trucks, respectively. According to the computational results, the majority of the loaded truck positions are performed by European plated trucks between seaports in Europe, railway terminals and order countries. In addition, there is some loaded European plated truck positions between seaports in Turkey and order countries. In other words, direct road freight transportation operations are mostly conducted by Turkish plated trucks between these type of ports and order countries.

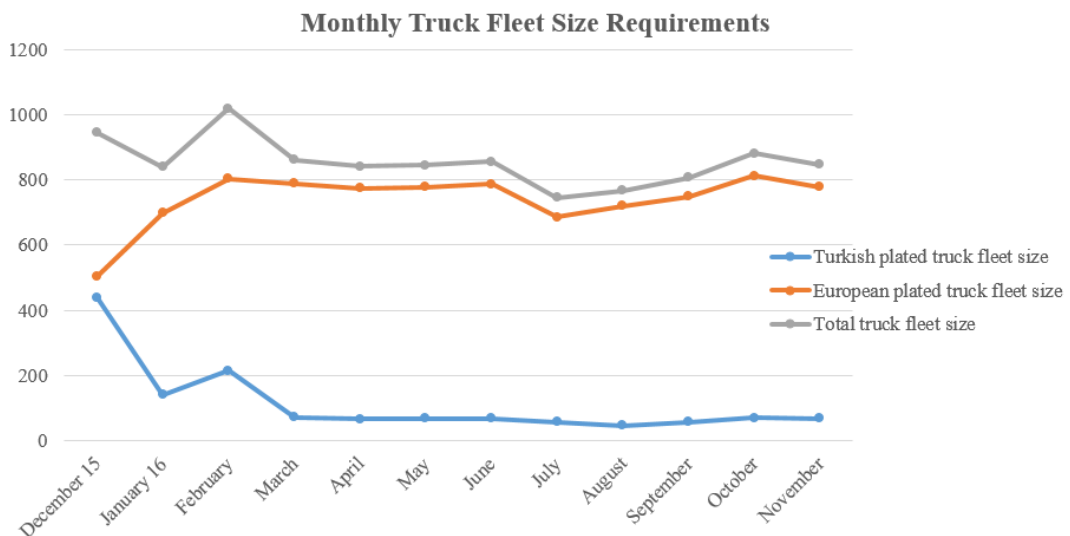


Figure 6.55 The monthly truck fleet size requirements with different plates on the road network

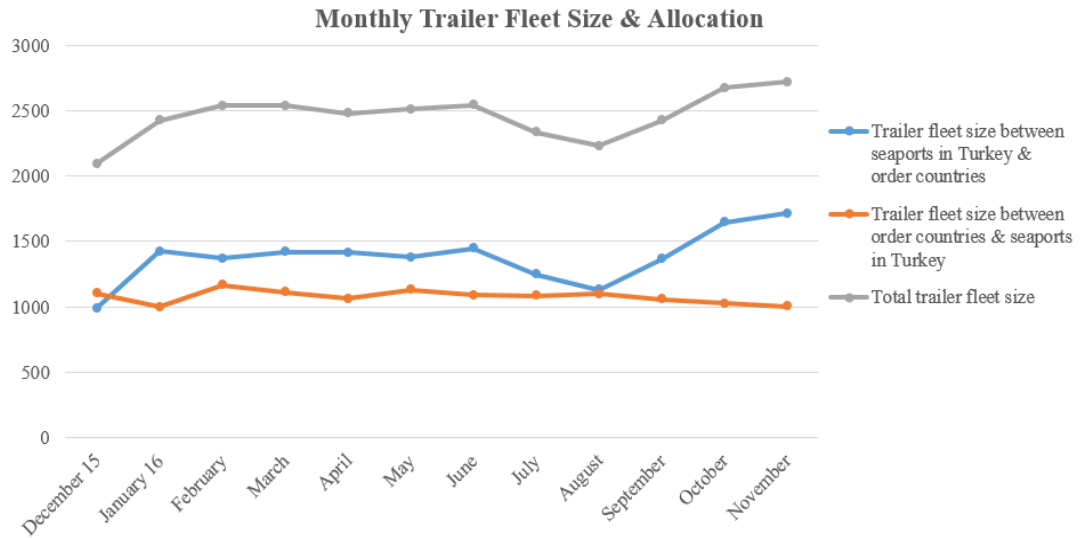


Figure 6.56 Monthly trailer fleet size requirements of different routes on intermodal logistics network

It should also be emphasized here that there is a balance between the loaded truck positions in the directions of importation and exportation at each month. The monthly truck and trailer fleet size requirements are also depicted in Figures 6.55 and 6.56. The truck/trailer fleet sizing results have shown that most of the European plated trucks should operate between railway stations and order countries. Furthermore, it is also displayed by these figures that the total trailer fleet size has larger quantities than truck fleet size as an expected result. The monthly variations of the truck and trailer fleet size requirements have similar characteristics. The large amount of truck fleet size composed of European plated trucks. Finally, most of the trailers should be allocated to seaports in Turkey rather than order countries.

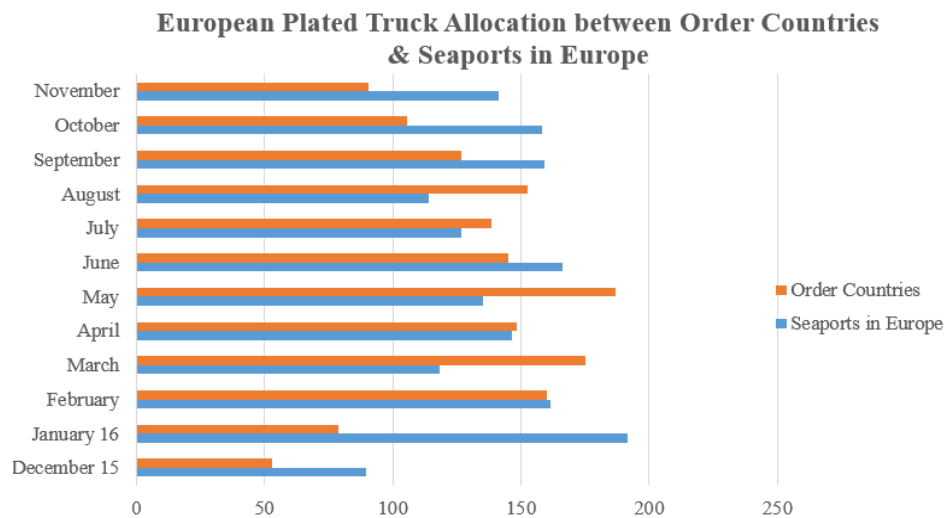


Figure 6.57 Monthly European plated truck allocation between seaports in Europe and order countries

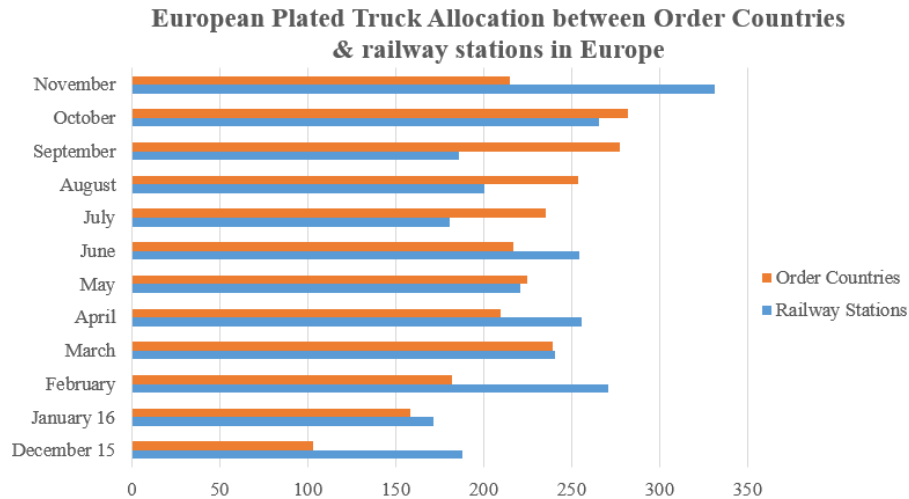


Figure 6.58 Monthly European plated truck allocation between railway stations and order countries

In Figures 6.57 to 6.60, fleet allocations of European and Turkish plated trucks are visualized. As it is emphasized before, appropriate fleet allocation may improve the fleet plans by decreasing the empty flows and associated costs. In Figures 6.57 and 6.58, the fleet allocations related to European plated trucks which operate between the seaports, railway stations in Europe and order countries are described. Similarly, Turkish and European plated truck fleet allocations among the seaports in Turkey and order countries are also designated by Figures 6.59 and 6.60. According to the outcomes of the truck fleet allocations, most of the European plated trucks should be allocated to seaports and railway stations in Europe rather than order countries. Conversely, Turkish plated trucks should be allocated to the order countries instead of seaports in Turkey as it is clearly seen from Figure 6.59.

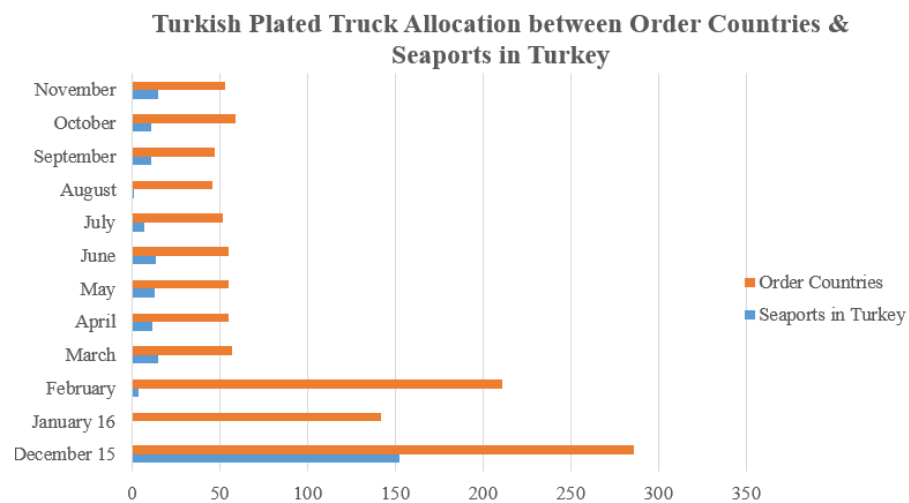


Figure 6.59 Monthly Turkish plated truck allocation between seaports in Turkey and order countries

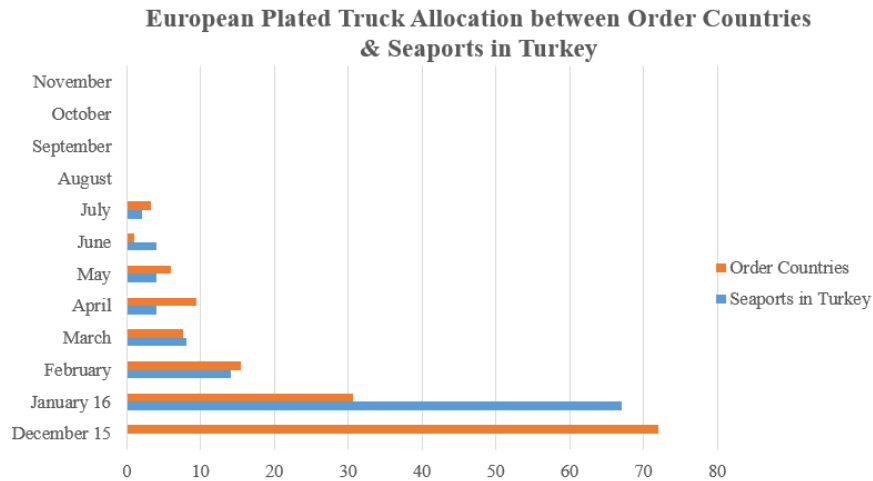


Figure 6.60 Monthly European plated truck allocation between seaports in Turkey and order countries

When the internal empty flows are evaluated, there is no empty trailer reposition between the seaports in Turkey and order countries since the long travel distances. Similarly, European and Turkish plated empty trucks are not repositioned internally between these ports and order countries. On the other hand, European plated empty trucks are generally repositioned internally between the seaports, railway terminals in Europe and order countries. The volume of empty flows among the order countries and railway stations is relatively higher. The amount of internal empty truck repositions between seaports in Europe and order countries is comparatively fewer. Moreover, most of the empty trucks are repositioned from seaports to order countries as displayed by Figure 6.61. On the contrary, the majority of European plated trucks are redistributed from order countries to railway stations as depicted in Figure 6.62.

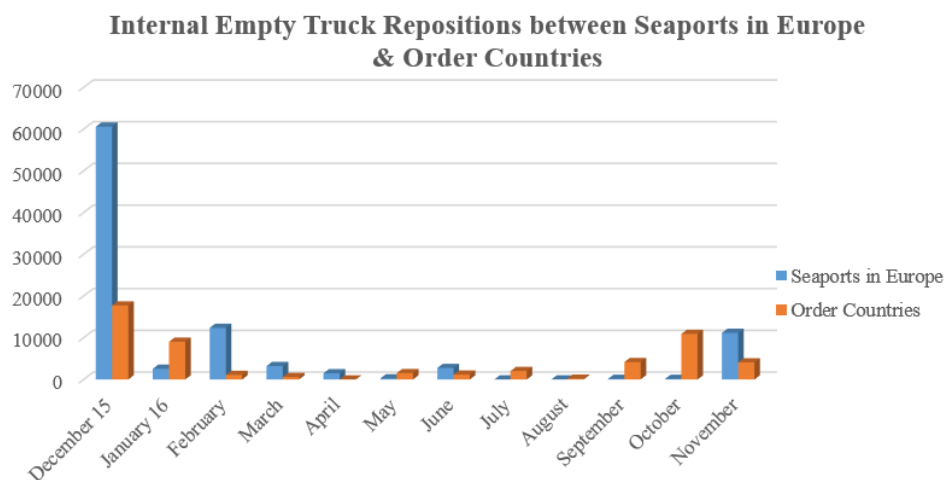


Figure 6.61 Amounts of monthly internal empty truck repositions (in kilometer) between the seaports in Europe and order countries

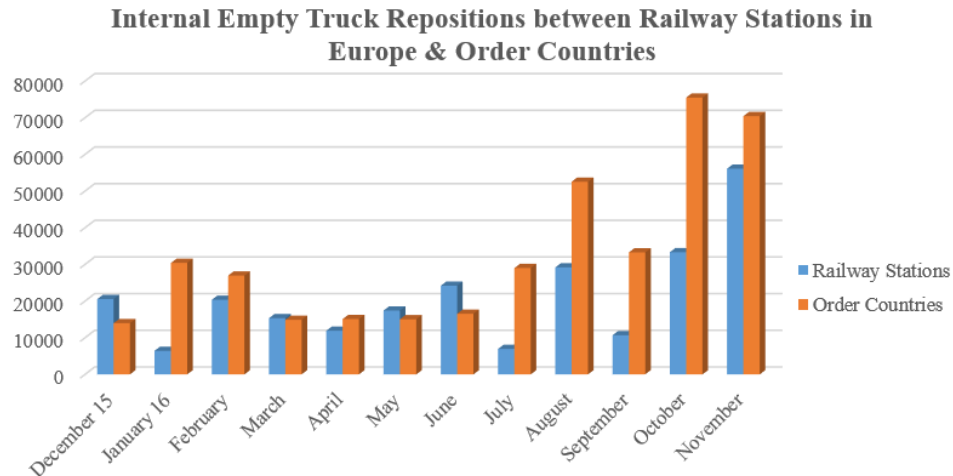


Figure 6.62 Amounts of monthly internal empty truck repositions (in kilometer) between the railway stations and order countries

The single objective and fuzzy multi-objective optimization results of truck/trailer fleet sizing are compared in Figures 6.63 and 6.64. When compared to deterministic case, both of the truck and trailer fleet size requirements will increase under probabilistic of freight demands. In addition, it is also obvious that fuzziness of the some model parameters may cause increases in truck/trailer fleet sizes. In case of simultaneous consideration of stochastic and fuzzy data, the fleet size will be its maximal level. It should be noted here that all of these single objective optimization results are provided based on minimizing the overall transportation costs. Besides, both of the truck and trailer fleet sizes will increase radically when the transit time and environmental goals are also undertaken.

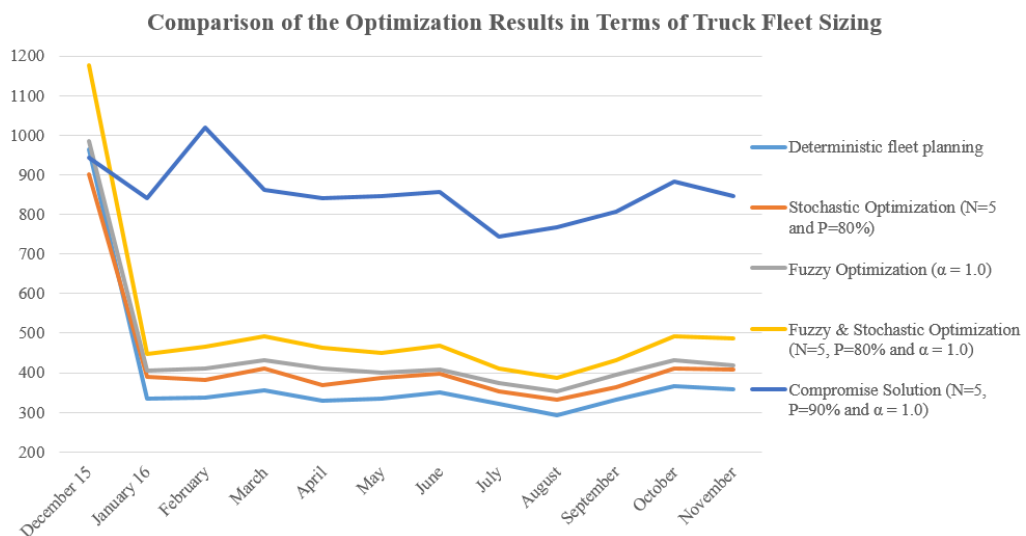


Figure 6.63 Comparison of the single and multi-objective truck fleet sizing results under uncertainty

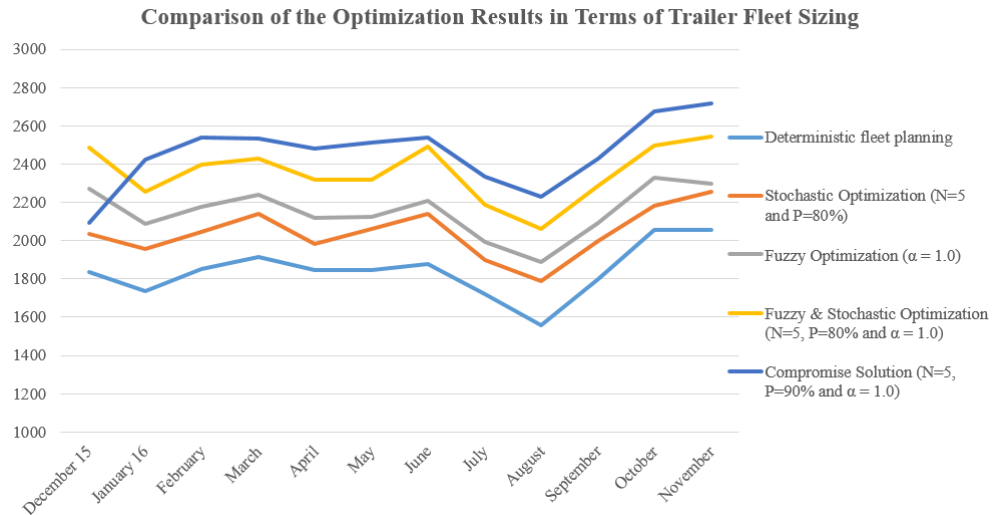


Figure 6.64 Comparison of the single and multi-objective trailer fleet sizing results under uncertainty

6.5.7.3 Module III: Periodic Truck/Trailer Inventories on the Intermodal Logistics Network and Fleet Expansion/Reduction Decisions

The periodic truck and trailer inventories on the different locations at the end of each month are shown by Figures 6.65 and 6.66, respectively. The truck inventory levels at the order countries and railway stations are comparatively higher than the seaports in Europe and Turkey. Opposite to the unstable Turkish plated truck inventories at the seaports in Turkey, European plated truck inventory levels have stable characteristic at the order countries, seaports and railway stations in Europe. Most of the European plated truck inventories will accumulate at the order countries and seaports in Europe to the end of the planning horizon.

Periodic Truck Inventories on the Intermodal Logistics Network

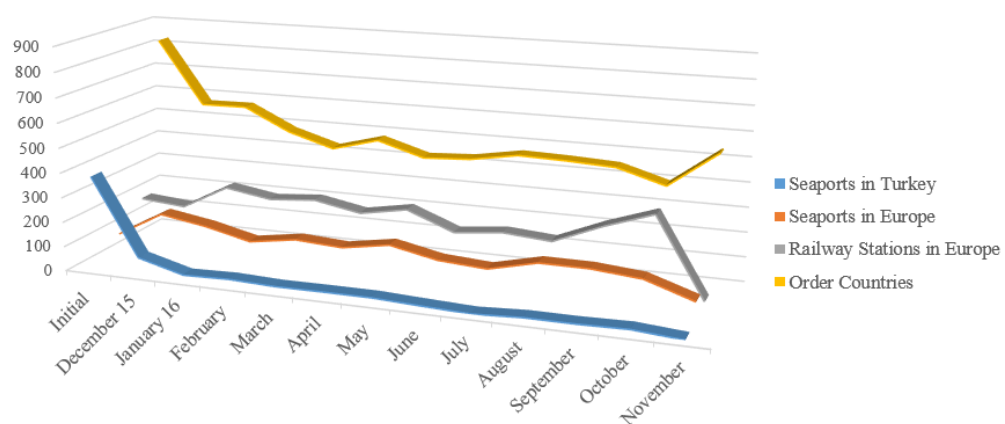


Figure 6.65 Periodic truck inventories at different nodes on the intermodal logistics network

Periodic Trailer Inventories on the Intermodal Logistics Network

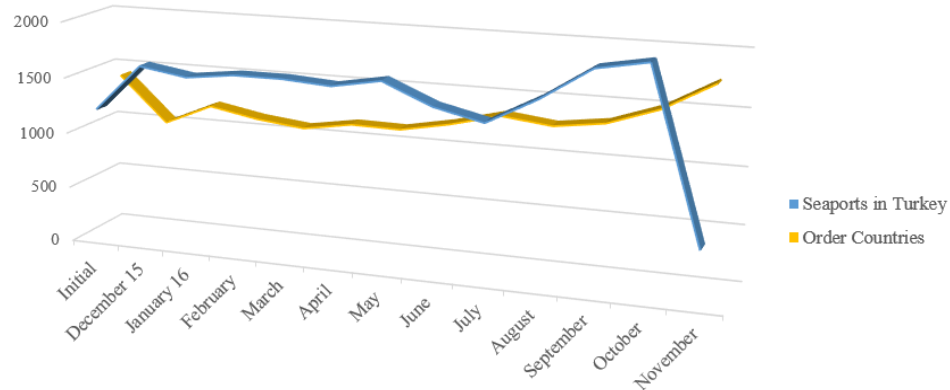


Figure 6.66 Periodic trailer inventories at the seaports in Turkey and order countries in Europe

In the compromise solution, there are many idle or inactive trucks and trailers as depicted in Figure 6.67. Actually, these trucks and trailers which are not utilized to perform loaded positions are called as idle. In fact, these trucks/trailers awaiting at different locations on the intermodal logistics can be used to conduct empty flows within the monthly time period. The number of idle Turkish plated trucks at the first three months are quite high. On the other hand, there is no idle European plated trucks throughout the planning horizon. Unfortunately, the level of idle trailers is larger than the idle trucks and tend to increase consistently along the planning horizon. The amounts of truck and trailer purchases and sales are presented in Table 6.24. According to this table, most of the Turkish plated trucks should be sold at Istanbul in the beginning of the planning period. Instead of Turkish plated trucks, European plated trucks should be generally used to realize the road freight transport operations between the seaports in Turkey and order countries.

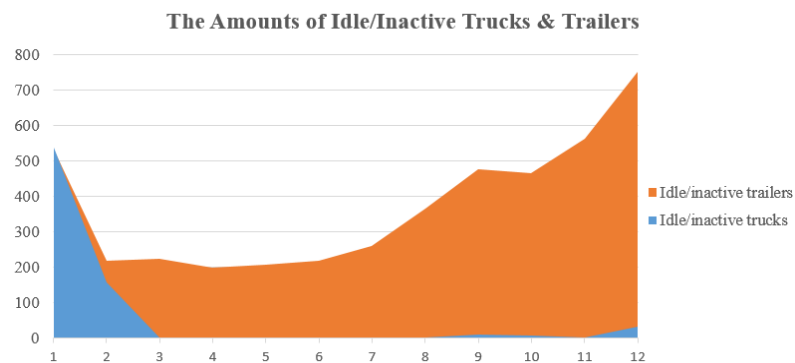


Figure 6.67 Amounts of idle trucks/trailers awaiting at different locations on the logistics network

Table 6.24 The quantities of truck/trailer purchases and sales at different locations

Months	Dec. 15	Jan. 16	Feb.	Mar.	Apr.	May	June	July	Augu.	Sep.	Oct.	Nov.
Purchasing New Turkish Plated Trucks & Sales of Second Hand Ones at Istanbul												
Purchase	-	-	-	-	0.356	0.071	-	-	10.92	6.82	1.24	-
Sale	607.7	82.7	142.8	3.88	-	-	9.49	6.74	-	-	-	-
Purchasing New Trailers & Sales of Second Hand Ones at Istanbul												
Purchase	14.83	118	-	-	42.09	71.34	-	9.19	182.56	346.4	234.6	-
Sale	-	-	28.11	47.68	-	-	101	-	-	-	-	1247
Purchasing New European Plated Trucks at Germany												
Region-1	-	-	-	-	-	-	-	-	-	-	-	-
Region-2	-	-	-	-	-	-	-	-	-	-	-	-
Region-3	19.23	-	-	-	-	-	-	-	-	6.582	-	-
Region-4	-	-	-	-	-	-	-	-	-	-	-	-
Region-5	25.56	57.3	-	-	-	-	-	-	-	22.82	-	-
Region-6	37.10	25	-	-	-	-	-	-	-	-	-	-
Region-7	-	-	-	-	-	-	-	-	-	-	2.81	-
Region-8	-	-	-	-	-	-	-	-	-	-	5.89	-
Region-9	65.01	32	23	25	30.15	26.01	4.21	27.7	24.29	24.54	0.52	-
Region-10	20.95	8.97	-	0.877	2.73	-	0.19	10.9	-	8.63	30.33	-
Sales of Second Hand European Plated Trucks at Germany												
Region-1	-	-	0.89	2.11	1.49	-	-	-	-	-	0.16	2.13
Region-2	27.82	0.58	0.401	0.052	-	-	0.165	-	-	-	0.94	2.08
Region-3	-	-	-	-	-	-	-	-	-	-	-	37
Region-4	3.76	18	37	38.35	21.48	17	51.22	-	-	-	42.24	26.97
Region-5	-	-	-	-	-	-	-	-	-	-	-	3.86
Region-6	-	-	-	-	-	-	37.16	-	-	-	-	148.5
Region-7	9.94	-	-	-	2.02	-	17.31	-	-	-	-	11.67
Region-8	4.61	0.08	-	-	3.39	-	-	-	-	-	-	8.173
Region-9	-	-	-	-	-	-	-	-	-	-	-	4.23
Region-10	-	-	-	-	-	-	-	-	-	-	-	8.24

However, it should be noted here that the logistics company should purchase and sale European plated trucks at the different locations in Germany so as to balance the variations of fleet size requirements at different months. Additionally, flexibility of truck/trailer purchases and sales may also decrease the usage rate of outsourcing option and empty truck/trailer repositions which are not desired by the logistics company.

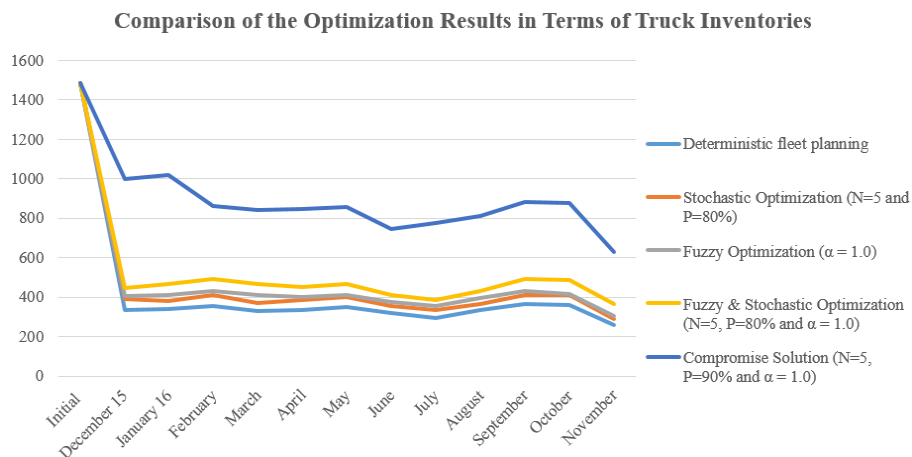


Figure 6.68 Comparison of the single and multi-objective truck inventory results under uncertainty

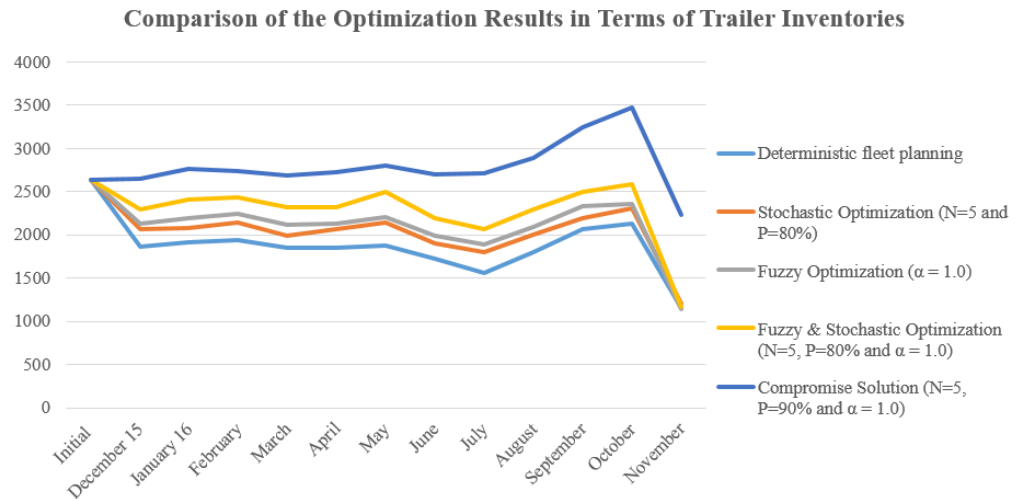


Figure 6.69 Comparison of the single and multi-objective truck inventory results under uncertainty

The comparison of the single and multi-objective optimization results related to the truck and trailer inventories can be visualized as in Figures 6.68 and 6.69. When all of the model parameters are assumed to be crisp, the minimal inventory levels are yielded. Even though the better reflection of real-life fleet plans by random freight demands and fuzzy transport capacities, these uncertainties may cause increases in both truck and trailer inventory levels. The quantities of idle truck and trailers are also analyzed for different optimization cases in Figure 6.70. In case of single objective optimization, i.e., minimization of overall transport costs, the number of idle trucks and trailers may decrease when the uncertainties embedded into the fleet planning problem are considered. On the other hand, significant accelerations in the amounts of idle resources may arise in case of fuzzy multi-objective optimization.

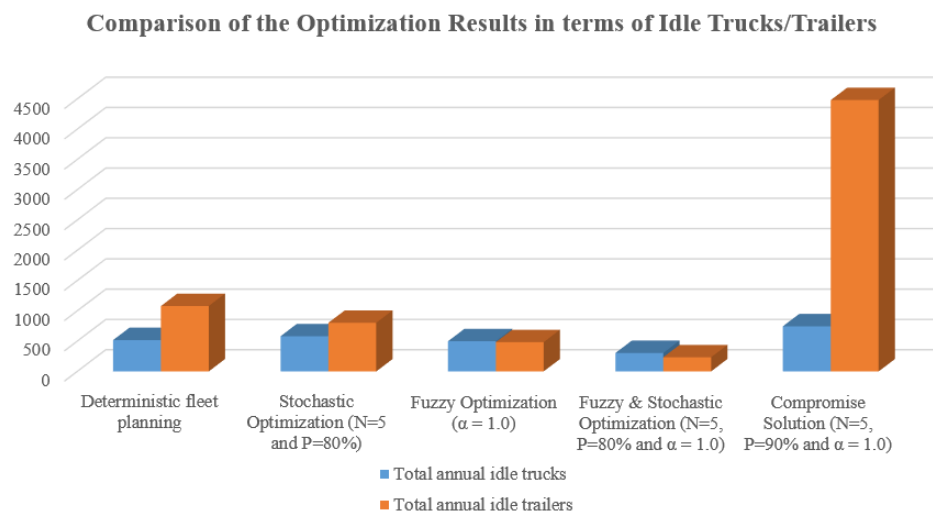


Figure 6.70 Comparison of single and multi-objective optimization results in terms of resource idleness

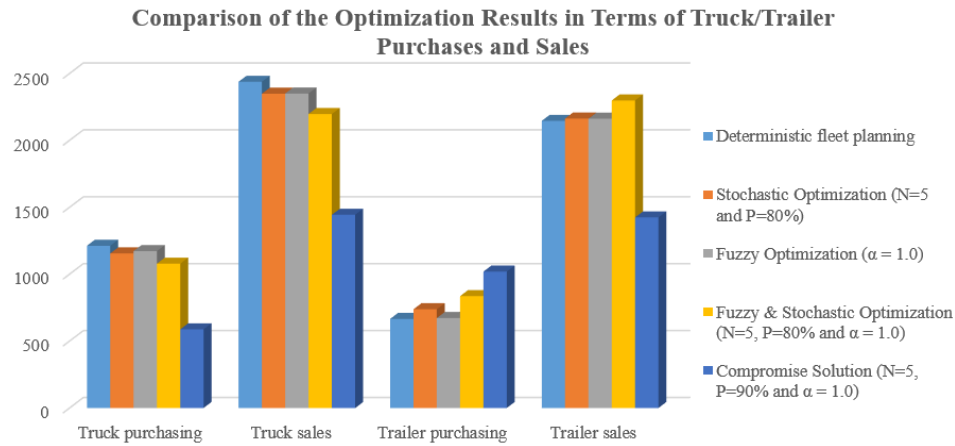


Figure 6.71 Comparison of single and multi-objective optimization results for truck/trailer purchases and sales under uncertainty

As depicted in Figure 6.71, the compromise solution can provide the minimal truck purchases/sales and trailer sales despite of the maximal trailer purchasing amounts. In contrast to the truck/trailer inventory levels, the quantities of truck purchases and sales may reduce when the different type of uncertainties are incorporated.

6.5.7.4 Module IV: External Empty Truck/Trailer Repositioning Issues

The amounts of external empty truck and trailer repositions can be portrayed as in Figures 6.72 and 6.73. There is no external empty truck/trailer repositions among the seaports themselves in Turkey. Similarly, no empty Turkish plated truck or trailer are repositioned externally between the order countries and seaports in Turkey.

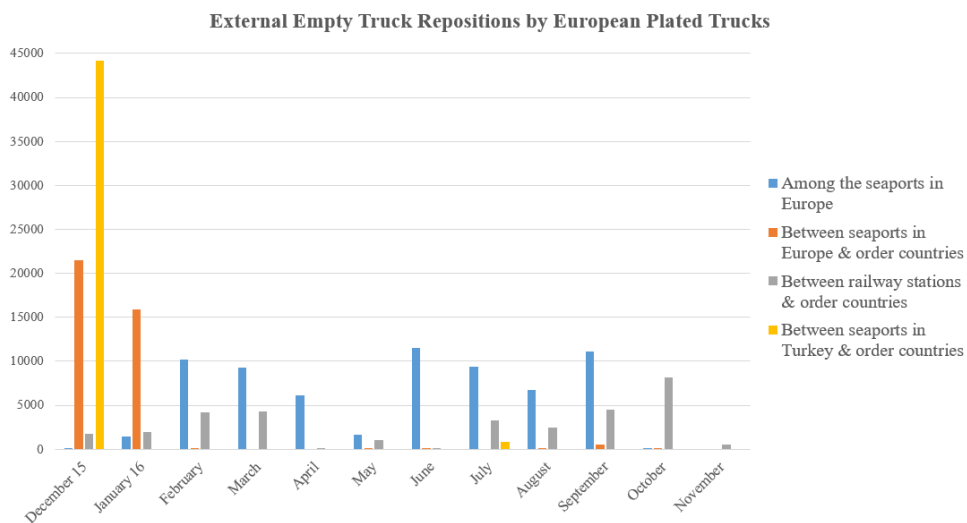


Figure 6.72 Amounts of external empty truck repositions (in kilometer) by European plated trucks between different locations

External Empty Truck/Trailer Repositions among the Order Countries

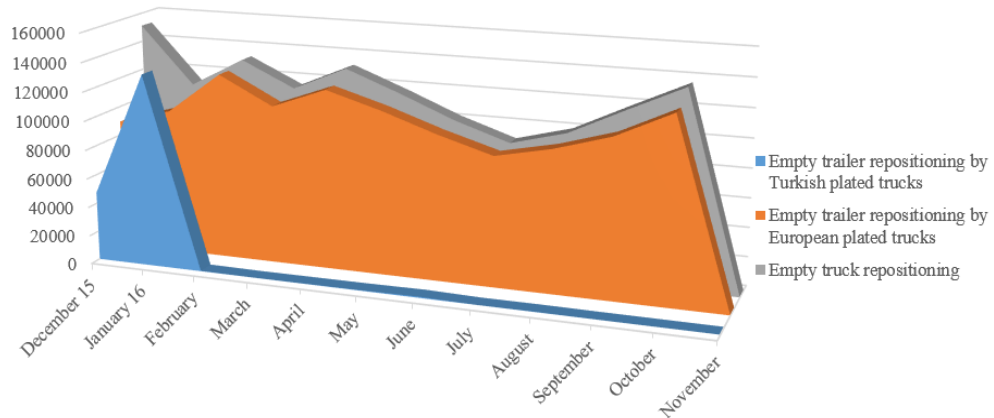


Figure 6.73 External empty truck and trailer repositions (in kilometer) among the order countries

According to Figure 6.72, European plated empty trucks are repositioned among the seaports themselves in Europe, between seaports, railway stations and order countries. At the beginning of the year, several European plated empty trucks are redistributed from the order countries to the seaports in Turkey in order to perform the loaded truck positions by direct road freight transportation. Furthermore, most of the external truck/trailer repositions will occur among the order countries themselves. Figure 6.73 displayed that large part of the external empty trailer repositions should be realized with European plated trucks. However, some empty trailer repositions are also accomplished by Turkish plated trucks at the first quarter of the year.

Comparison of the Optimization Results in Terms of External Empty Truck Flows

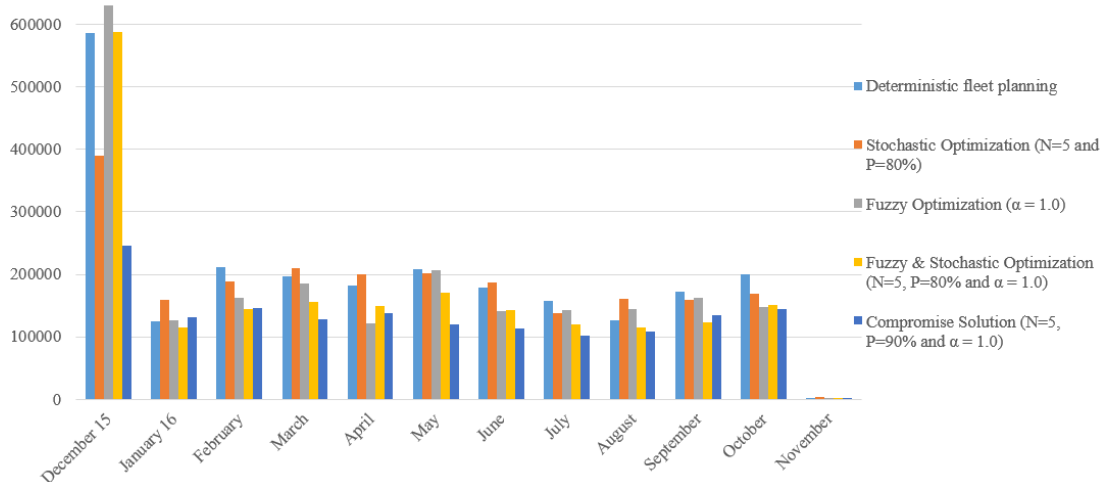


Figure 6.74 Comparison of the single and multi-objective optimization results for external empty truck repositioning under uncertainty

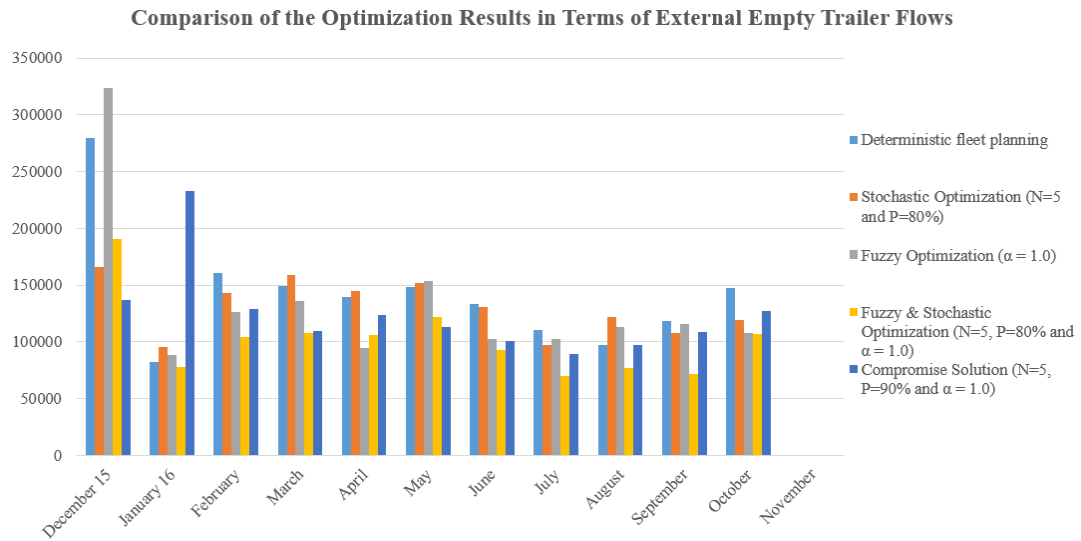


Figure 6.75 Comparison of the single and multi-objective optimization results for external empty trailer repositioning under uncertainty

The single and multi-objective optimization results regarding the external empty truck/trailer repositions are compared in Figures 6.74 and 6.75. In the deterministic fleet planning model, both of the empty truck and trailer transfers are generally higher than the stochastic and fuzzy optimization cases. Furthermore, it is expressed by the company experts that compromise solution contains acceptable level of external empty flows. According to the comparison of the internal empty truck flows as depicted in Figure 6.76, deterministic and fuzzy fleet planning models have the largest repositioning quantities. Again, the compromise solution has the minimal level of internal empty truck flows which makes this solution more applicable.

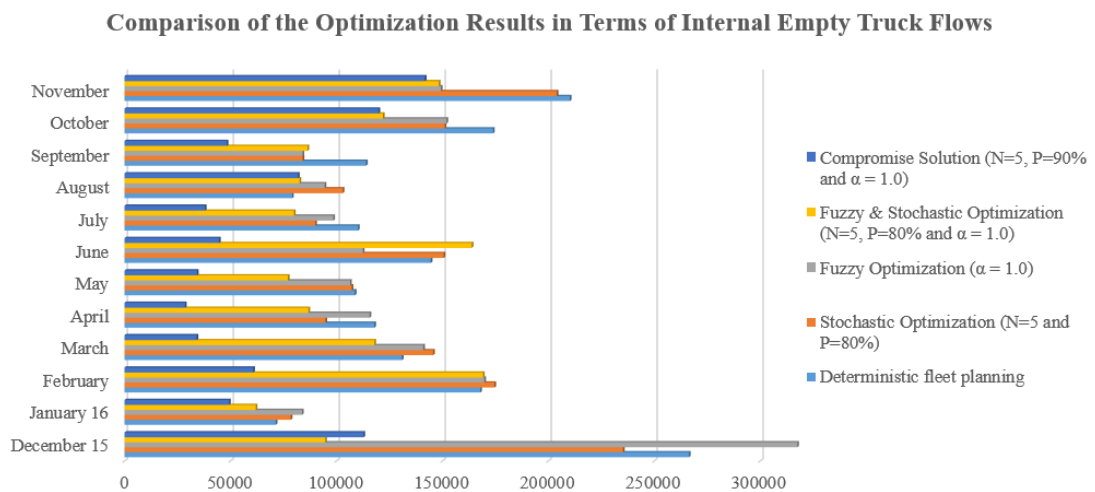


Figure 6.76 Comparison of the single and multi-objective optimization results for internal empty truck repositioning under uncertainty

6.6 Chapter Summary

In this chapter, a DSS depending upon a novel fuzzy-stochastic optimization model is developed to solve a multi-objective, multi-mode, multi-resource and multi-period fleet planning problems by considering load planning, fleet size/composition, fleet allocation, fleet expansion/reduction, truck/trailer inventories and empty truck/trailer repositioning issues simultaneously. The proposed holistic fleet planning model aims at minimizing the overall transport costs throughout the intermodal logistics network. In addition to the cost objective, maximal customer service level satisfaction is also targeted by minimizing the total road, marine and railway transit times. Besides, the amounts of CO₂ emissions generated from the usage of different modes of transport are also optimized so as to provide environmental conscious fleet plans to the company experts. The different uncertainty categories such as randomness and fuzziness are taken into account altogether by the developed DSS. In fact, the probabilistic import/export freight demands of the order countries and fuzzy transport capacities of Ro-Ro vessels, transit times, cost terms, number of working days at the order countries etc. are undertaken by chance-constraint programming and fuzzy mathematical programming approaches. Finally, in order to handle these conflicting objectives simultaneously and obtain compromise solutions under different uncertainty levels, a weighted additive fuzzy goal programming approach is employed. The validity and practicality of the proposed DSS are proved based on a real-life application in large-sized international logistics company of Turkey. The computational results have shown that effective and efficient load plans, truck/trailer fleet sizes and empty vehicle repositions can be generated by making use of the developed DSS. It is also revealed that logistics companies can provide sustainable competitive advantage by improving their fleet planning mechanisms which may contribute to the high level of customer satisfaction in addition to the possible cost reductions and ecological improvements. In the future, the proposed holistic intermodal fleet planning model may be extended by incorporating the tactical fleet replacement decisions and also some operational level decisions such as scheduling of the trucks and Ro-Ro vessels, load consolidation at the terminals/hubs. Additionally, more focuses on the other essential components of the proposed DSS, i.e., database integration and user interface design, can be given in the future works.

CHAPTER SEVEN

CONCLUSIONS

7.1 Summary of the Thesis and Concluding Remarks

This thesis dealt with the transportation network optimization and fleet planning problems in supply chains under fully uncertain environments. First of all, different types of balanced and unbalanced fuzzy transportation and transshipment problems with fuzzy decision variables are produced and solved in order to illustrate the validity and practicality of the proposed CFA based direct and indirect solution approaches. In contrast to the compared fuzzy mathematical programming methods, the proposed approaches maintain information efficient and applicable results since taking into account the supplementary information represented by the requisite crisp or fuzzy constraints. In detail, the decision maker can be supported with various fuzzy efficient solutions under different uncertainty levels (α -cuts) and risk attitudes. According to the computational analysis, it has been observed that more reliable and relatively more precise solutions can be generated by the proposed approaches for risk-averse and partially risk-averse decision makers. Similar to the other methods, proposed approaches can also effectively offer fuzzy decisions on transportation amounts including high degree of uncertainty for risk seekers.

Secondly, apart from the proposed CFA based approaches, a new (α, β) -parametric method is developed based on standard fuzzy arithmetic operations and applied to a generic fully fuzzy reverse logistics network design model whose parameters and decision variables are represented by fuzzy numbers. Comparative analyses are also performed with the current approaches in the literature for testing the computational efficiency, solution quality and ease of use. The closed-form mathematical representations of both compared approaches and our method are also formulated for easily handling by algebraic modeling languages for fuzzy optimization. The optimization results have shown that compared methods delivered similar outcomes with the proposed method for a risk-seeking decision maker.

Thirdly, before risk management in a lead/acid battery CLSC, the deterministic, stochastic, fuzzy and the hybrid models are compared in an aggregated manner. It has

shown that stochasticity of battery demands may cause increases in total cost values. Fortunately, when the fuzzy data is also taken into account by the hybrid model, total cost of the system may decrease. Besides, simultaneous consideration of different uncertainty categories in data may provide increases in total collection coverage when compared to deterministic case. But, total quantities of collected batteries resulting from the hybrid model are fewer than the stochastic optimization results. After managing the financial and collection coverage risks throughout the CLSC, the computational results have demonstrated that total expected CLSC cost may increase and total expected collection coverage may decrease. Furthermore, results of different risk metrics have suggested that using downside risk model with fuzzy targets will be the best choice in terms of computational efficiency, handling uncertainty and solution quality. In detail, percent of high coverage and low cost scenarios are superior to the variability index and conditional value at risk measures.

Fourthly, results of deterministic multi-mode load planning model have revealed that intermodal transportation is the most effective and efficient way of freight carriage and may contribute to all of the economic, customer satisfaction and environmental goals. Among the different multi-objective optimization techniques, compromise programming method with Chebyshev and Pythagorean distance metrics can generate better results in terms of the total transport cost and environmental impact objectives. Moreover, relatively shorter transit times can be found by applying interactive fuzzy goal programming approach. According to the scenario analysis, the availability of block train services, marine transport costs by the other logistics service providers' Ro-Ro vessels are the most influential factors on total cost, total transit time and CO2 emission objectives. The experts of EKOL Logistics Inc. have announced that appropriate load plans can be generated via the proposed integer programming model. Finally, it is also discovered that sustainable competitive advantage can be reached by improving the logistics company's multimodal transportation planning mechanism with high level of customer satisfaction, environmental sensitivity and minimal cost.

Lastly, an integrated chance-constrained and fuzzy mathematical programming based solution approach is employed to an intermodal fleet planning problem. The computational results of the fuzzy-stochastic holistic fleet planning model have shown

that external empty truck/trailer repositions can provide major reductions in total transport cost goal although they do not have substantial impact on the transit time and environmental goals. When the deterministic, stochastic, fuzzy and fuzzy & stochastic optimization results are compared, the truck/trailer fleet sizes and their related inventories will increase under probabilistic freight demands and fuzzy transport capacities. On the other hand, the amounts of idle trucks/trailers, purchasing and sales quantities will decrease when the different types of uncertainties such as randomness and fuzziness are taken into account simultaneously.

7.2 Original Contributions of the Thesis

To sum up, the research contributions accomplished with this Ph.D. thesis can be explained as followings:

- A novel CFA based solution method is developed for indirect solution of fully fuzzy transportation and transshipment problems with fuzzy decision variables. To the best of our knowledge, this method is the first one in the literature which applies CFA concept to transform fully fuzzy mathematical programming models into the crisp equivalent form. This method is also able to handle risk tolerance by performing the fuzzy arithmetic operations with an additional information. Therefore, risk-free, more reliable and applicable solutions can be achieved according to the attitude of decision maker toward risk (risk-averse, risk-neutral and risk-seeker). Moreover, since the proposed method is based on α -cuts (alpha parametric approach) it is possible to generate various fuzzy efficient solutions under different uncertainty levels. Because of the structure of three dimensional membership function associated with fuzzy relation among the base variables of fuzzy components, this method is applicable to both symmetric and non-symmetric triangular fuzzy numbers. Besides, it does not need to utilize any secondary approach like fuzzy ranking procedure. Opposite to the most of the current methods which cannot handle intersections between different fuzzy membership functions, i.e., they provide only infeasible solutions, the proposed method is able to consider intersections effectively by making use of requisite crisp or fuzzy constraints.

- A new CFA based decoding procedure with a metaheuristic application is presented for direct solution of fully fuzzy balanced and unbalanced transportation cases. In fact, this fuzzy decoding procedure is needed due to the usage of priority-based encoding method for solution representation of the transportation trees. By the proposed approach, there is no need to balance the unbalanced transportation case by introducing a dummy node on the solution vector. This improvement yields more efficient and effective way of encoding/decoding procedures and also computational efficiency. Additionally, equal fuzzy transportation cost or equal defuzzified transportation cost issues are also taken into account for better reflection of real-life transportation applications. The fuzzy arithmetic operations are performed with the help of requisite constraints which correspond to the crisp or fuzzy relations between the base variables of the fuzzy terms. A defuzzification technique is also utilized for ranking fuzzy transportation costs and calculate the fuzzy fitness function values. Then, the decoding procedure is embedded into the particle swarm optimization algorithm. By making use of this direct solution approach, more computational and information efficient solutions can be produced without any fuzzy to crisp transformation process.
- In addition to the above CFA based direct and indirect solution approaches, a new (α, β) -parametric method which is mainly based on α -cut representation of fuzzy intervals is proposed for solving fully fuzzified reverse logistics network design problems. Fortunately, this transformation method does not require to use CFA operations into the conversion process while incorporating the decision maker's attitude toward risk.
- A new scenario-based stochastic and possibilistic mixed integer programming model is developed for a multi-objective lead/acid battery closed-loop supply chain network design under the consideration of financial and collection risk measures. By the proposed hybrid model, the data uncertainties in the form of randomness and fuzziness can be handled simultaneously for better reflection of the real-life applications where the different uncertainty types might occur altogether. Afterwards, several risk management metrics, i.e., variability index,

downside risk and conditional value at risk are integrated within the proposed hybrid model. Differently from the available literature where the crisp risk measures are implemented in general, target/threshold values are considered as fuzzy and described by their own possibility distribution while formulating the fuzzy version of the downside risk model.

- A DSS based on a novel fuzzy & stochastic mathematical programming model is developed for a real world intermodal fleet management system of a large-sized international logistics company in Turkey. By the proposed multi-objective, multi-mode, multi-resource (trucks/trailers) and multi-period sustainable fleet planning model, not only fleet sizing and composition problems but also the fleet allocation, load planning, fleet expansion/reduction, periodic truck/trailer inventories and empty truck/trailer repositioning issues can be determined. In fact, the proposed DSS is able to handle the perspectives and goals of different decision makers with strategic, tactical and operational level decisions. In addition to minimize the total transportation costs, optimization of total transit times and CO₂ emission values are also intended in order to maximize customer satisfaction and environmental consciousness. Apart from the existing intermodal freight transportation planning models in the literature, both import and export flows of the freights are taken into account. Furthermore, consolidation operations are also considered at the transshipment seaports and railway stations. Differently from the available literature related to empty vehicle repositioning problem, the empty flows of the trucks and trailers are divided into two categories namely internal and external empty repositions. Different types of plates, i.e., Turkish or European plated trucks and relevant cabotage limitations in Europe are also take into consideration within the proposed model for performing these empty flows.

7.3 Future Research Directions

There may exist several possible research extensions for this thesis. Hereafter, some of the future works can be summarized as follows:

- Except the fully fuzzy transportation problems, the developed CFA based direct and indirect solution methodologies can also be applied to solve any other fully fuzzy linear programming problems in the literature. Specifically, the proposed linear programming based indirect solution method and meta-heuristic based direct solution approach can first be adapted for the solution of fully fuzzy supply chain planning and logistics network design problems.
- The proposed (α, β) -parametric transformation method which does not need to utilize CFA operations can be translated into a direct solution approach by using again a decoding algorithm with meta-heuristic applications or a fuzzy simplex type algorithm. Therefore, instead of basic reverse logistics network design problems, large scaled and more complicated closed-loop supply chain planning models with multiple objectives, time periods, products can be solved within a reasonable computational time.
- In the future, a multiple objective optimization technique can be employed in order to find compromise solutions for the examined lead-acid battery closed-loop supply chain network design problem. In other words, Pareto optimal solutions can be achieved under financial and collection risk assessments. Apart from the well-known risk management tools, i.e., downside risk, variability index, conditional value at risk models etc. a novel risk management metric depending upon variability, targets and losses can also be developed.
- The proposed multi-mode load planning and intermodal fleet planning models can be extended by adding some other strategic level decisions such as terminal location selection, terminal layout design and multimodal logistics network design issues. Moreover, fleet replacement and load consolidation problems which correspond to the tactical level decisions can also be incorporated within the proposed models. Finally, a dynamic optimization model which integrates the operational level issues such as truck routing and scheduling of block trains and Ro-Ro vessels can be scheduled as future studies.

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APPENDICES

APPENDIX A - NOMENCLATURE OF CHAPTERS 5 AND 6

Appendix A1: Logistics network notation

Indices & sets:

- $i \in I$ seaports in Turkey for import/export marine transport operations, $I = \{1, \dots, |I|\}$
 $j, j', j^* \in J$ seaports in Europe for import/export marine transport operations, $J = \{1, \dots, |J|\}$
 $k, k', k^* \in K$ rail stations in Europe for import/export railway transport operations, $K = \{1, \dots, |K|\}$
 $l \in L$ order countries in Europe (aggregated customers), $L = \{1, \dots, |L|\}$
 $t \in T$ monthly time period, $T = \{1, \dots, |T|\}$

Marine transport network subsets:

- $(i, j) \in L_{ij}$ set of marine links where import/export transport operations can be performed by only other logistics service providers' Ro-Ro vessels,
 $(i, j) \in C_{ij}$ set of marine links where import/export transport operations can be performed by only the company-owned Ro-Ro vessels,
 $(i, j) \in B_{ij}$ set of marine links where import/export transport operations can be performed by both company-owned and other logistics service providers' Ro-Ro vessels,
 $j' \in T_j$ set of transshipment seaports where the extra freights can be loaded/unloaded during the transportation services,
 $j^* \in \gamma_j$ set of main origin and destination seaports including at least one transshipment seaport on its marine route,
 $j \in D_j$ set of seaports in Europe which are directly connected with a railway station,

Railway transport network subsets:

- $(j, k) \in L_{jk}$ set of rail lines where import/export transport operations can be performed by only public train services,
 $(j, k) \in C_{jk}$ set of rail lines where import/export transport operations can be performed by only chartering block trains,
 $(j, k) \in B_{jk}$ set of rail lines where import/export transport operations can be performed by both block train and public train services,
 $k' \in T_k$ set of transshipment stations which also have railway connections with other main stations,
 $k^* \in G_k$ set of main origin and destination stations including at least one transshipment station on its rail route,
 $k \in D_k$ set of railway stations which are directly connected with a seaport in Europe,

Road transport network subsets:

- $l \in PR_L$ set of order countries where newly purchased European plated trucks can join or second hand trucks leave the intermodal transportation system,
 $i \in PR_i$ set of seaports in Turkey where newly purchased Turkish plated trucks and trailers can join or second hand trucks/trailers leave the intermodal transportation system,
 $l \in G_l$ set of order countries that can be served by road freight transport from the main railway stations, $k^* \in G_k$ involving railway transshipments
-

Appendix A2: Deterministic, stochastic and fuzzy parameters

Fuzzy cost parameters:

- $\widetilde{C}o_{ij}^{exp}$ marine transport cost per TU of export operation by company owned Ro-Ro vessels on marine link $(i, j) \notin L_{ij}$
- $\widetilde{C}o_{ji}^{imp}$ marine transport cost per TU of import operation by company owned Ro-Ro vessels on marine link $(j, i) \notin L_{ji}$
- $\widetilde{C}p_{ij}^{exp}$ marine transport cost per TU of export operation by other logistics service providers' Ro-Ro vessels on marine link $(i, j) \notin C_{ij}$
- $\widetilde{C}p_{ji}^{imp}$ marine transport cost per TU of import operation by other logistics service providers' Ro-Ro vessels on marine link $(j, i) \notin C_{ji}$
- $\widetilde{C}b_{jk}^{exp}$ railway transport cost per block train chartered for export operation on rail line $(j, k) \notin L_{jk}$
- $\widetilde{C}b_{kj}^{imp}$ railway transport cost per block train chartered for import operation on rail line $(k, j) \notin L_{kj}$
- $\widetilde{C}p_{jk}^{exp}$ railway transport cost per TU of export operation by public trains on rail line $(j, k) \notin C_{jk}$
- $\widetilde{C}p_{kj}^{imp}$ railway transport cost per TU of import operation by public trains on rail line $(j, k) \notin C_{jk}$
- $\widetilde{C}p_{k'k^*}^{exp}$ railway transport cost per TU of export operation by public trains on rail line $(k', k^*) \mid k' \in T_k \text{ and } k^* \in G_k$
- $\widetilde{C}p_{k^*k'}^{imp}$ railway transport cost per TU of import operation by public trains on rail line $(k^*, k') \mid k^* \in G_k \text{ and } k' \in T_k$
- $\widetilde{S}C_{ilt}^{exp}$ outsourcing cost per TU of export operation from seaport in Turkey i to order country l in time period t
- $\widetilde{S}C_{lit}^{imp}$ outsourcing cost per TU of import operation from order country l to seaport in Turkey i in time period t
- $\widetilde{C}r$ road freight transport cost per km of per TU by European or Turkish plated trucks for both import/export operations
- $\widetilde{R}C^v$ empty repositioning cost per km of European or Turkish plated trucks
- $\widetilde{R}C^{Tr}$ empty repositioning cost per km of trailers
- $\widetilde{O}W C_{Euro}^{Truck}$ monthly fixed ownership cost per European plated truck
- $\widetilde{O}W C_{Turk}^{Truck}$ monthly fixed ownership cost per Turkish plated truck
- $\widetilde{O}W N^{Trail}$ monthly fixed ownership cost per trailer
- $\widetilde{P}C V^E$ annual cost of purchasing a new European plated truck
- $\widetilde{P}C V^T$ annual cost of purchasing a new Turkish plated truck
- $\widetilde{P}C T$ annual cost of purchasing a new trailer
- $\widetilde{S}V^E$ revenue obtained from the sales of a second-hand European plated truck
- $\widetilde{S}V^T$ revenue obtained from the sales of a second-hand Turkish plated truck
- $\widetilde{S}T$ revenue obtained from the sales of a second-hand trailer

Deterministic road, marine and rail travel distances:

- d_{il}^r road travel distance between seaports in Turkey $i \in I$ and order country $l \in L$
- d_{li}^r road travel distance between order country $l \in L$ and seaports in Turkey $i \in I$
- d_{jl}^r road travel distance between seaports in Europe $j \in J$ and order country $l \in L$
- d_{lj}^r road travel distance between order country $l \in L$ and seaports in Europe $j \in J$
- d_{kl}^r road travel distance between railway stations $k \in D_k \cup T_k$ and order country $l \in L$
- d_{lk}^r road travel distance between order country $l \in L$ and railway stations $k \in D_k \cup T_k$
- d_{jk}^r road travel distance between seaports in Europe $j \in J$ and rail stations $k \in K$ for empty flows

Appendix A2: Deterministic, stochastic and fuzzy parameters (Cont.)

d_{kj}^r	road travel distance between rail stations $k \in K$ and seaports in Europe $j \in J$ for empty flows
$d_{j'j}^r$	road travel distance among the seaports themselves in Europe $j \in J$ for empty flows
$d_{l'l}^r$	road travel distance among the order countries themselves $l \in L$ for empty flows
$d_{i'i}^r$	road travel distance among the seaports themselves in Turkey $i \in I$ for empty flows
$d_{k'k}^r$	road travel distance among the railway stations themselves in Europe $k \in K$ for empty flows
$d_{k^*l}^r$	road travel distance between rail stations $k^* \in G_k$ and order country $l \in G_l$
$d_{lk^*}^r$	road travel distance between order country $l \in G_l$ and rail stations $k^* \in G_k$
d_{ij}^m	marine travel distance between seaports in Turkey and Europe, $(i, j) \in L_{ij} \cup C_{ij} \cup B_{ij}$
d_{ji}^m	marine travel distance between seaports in Europe and Turkey, $(j, i) \in L_{ji} \cup C_{ji} \cup B_{ji}$
d_{jk}^t	railway travel distance between seaports in Europe and rail stations, $(j, k) \in L_{jk} \cup C_{jk} \cup B_{jk}$ and $k \notin G_k$
d_{kj}^t	railway travel distance between rail stations and seaports in Europe, $(k, j) \in L_{kj} \cup C_{kj} \cup B_{kj}$ and $k \notin G_k$
$d_{k'k^*}^t$	railway travel distance between transshipment and main stations, $(k', k^*) \in L_{k'k^*}$, $k' \in T_k$ and $k^* \in G_k$
$d_{k^*k'}^t$	railway travel distance between main and transshipment stations, $(k^*, k') \in L_{k^*k'}$, $k' \in T_k$ and $k^* \in G_k$

Fuzzy road, marine and rail transit times:

$\tilde{T}_{il}^r$	road transit time between seaports in Turkey $i \in I$ and order country $l \in L$
$\tilde{T}_{li}^r$	road transit time between order country $l \in L$ and seaports in Turkey $i \in I$
$\tilde{T}_{jl}^r$	road transit time between seaports in Europe $j \in J$ and order country $l \in L$
$\tilde{T}_{lj}^r$	road transit time between order country $l \in L$ and seaports in Europe $j \in J$
$\tilde{T}_{kl}^r$	road transit time between railway stations $k \in D_k \cup T_k$ and order country $l \in L$
$\tilde{T}_{lk}^r$	road transit time between order country $l \in L$ and railway stations $k \in D_k \cup T_k$
$\tilde{T}_{jk}^r$	road transit time between seaports in Europe $j \in J$ and rail stations $k \in K$
$\tilde{T}_{kj}^r$	road transit time between rail stations $k \in K$ and seaports in Europe $j \in J$
$\tilde{T}_{j'j}^r$	road transit time among the seaports themselves in Europe $j \in J$
$\tilde{T}_{l'l}^r$	road transit time among the order countries themselves $l \in L$
$\tilde{T}_{i'i}^r$	road transit time among the seaports themselves in Turkey $i \in I$
$\tilde{T}_{k'k}^r$	road transit time among the railway stations themselves in Europe $k \in K$
$\tilde{T}_{k^*l}^r$	road transit time between rail stations $k^* \in G_k$ and order country $l \in G_l$
$\tilde{T}_{ij}^m$	marine transit time between seaports in Turkey and Europe, $(i, j) \in L_{ij} \cup C_{ij} \cup B_{ij}$
$\tilde{T}_{ji}^m$	marine transit time between seaports in Europe and Turkey, $(j, i) \in L_{ji} \cup C_{ji} \cup B_{ji}$
$\tilde{T}_{jk}^t$	railway transit time between seaports and rail stations, $(j, k) \in L_{jk} \cup C_{jk} \cup B_{jk}$ and $k \notin G_k$
$\tilde{T}_{kj}^t$	railway transit time between rail stations and seaports in Europe, $(k, j) \in L_{kj} \cup C_{kj} \cup B_{kj}$ and $k \notin G_k$
$\tilde{T}_{jk'}^t$	railway transit time between seaports in Europe and transshipment rail stations, $(j, k') \in C_{jk'}$ and $k' \in T_k$
$\tilde{T}_{k'j}^t$	railway transit time between transshipment rail stations and seaports in Europe, $(k', j) \in C_{k'j}$ and $k' \in T_k$
$\tilde{T}_{k'k^*}^t$	railway transit time between transshipment and main stations, $(k', k^*) \in L_{k'k^*}$, $k' \in T_k$ and $k^* \in G_k$
$\tilde{T}_{k^*k'}^t$	railway transit time between main and transshipment rail stations, $(k^*, k') \in L_{k^*k'}$, $k' \in T_k$ and $k^* \in G_k$

Fuzzy environmental impact parameters:

$\widetilde{CO}_2^M$	amount of CO ₂ emissions (in kg) by marine transport services per km of per TU
$\widetilde{CO}_2^R$	amount of CO ₂ emissions (in kg) of loaded truck positions by road transport per km of per TU
$\widetilde{CO}_2^{RE}$	amount of CO ₂ emissions (in kg) of empty truck repositions by road transport per km
$\widetilde{CO}_2^T$	amount of CO ₂ emissions (in kg) by railway transport services per km of per TU

Appendix A2: Deterministic, stochastic and fuzzy parameters (Cont.)

Stochastic transport demands and their parameters:

- De_{ilt}^{exp} random export transport demand of order country l from seaport in Turkey i in time period t
 De_{lit}^{imp} random import transport demand of order country l to seaport in Turkey i in time period t
 μ_{ilt}^{exp} mean value of the export transport demand, De_{ilt}^{exp} (in TUs)
 μ_{lit}^{imp} mean value of the import transport demand, De_{lit}^{imp} (in TUs)
 σ_{ilt}^{exp} standard deviation of the export transport demand, De_{ilt}^{exp} (in TUs)
 σ_{lit}^{imp} standard deviation of the import transport demand, De_{lit}^{imp} (in TUs)
 α_{ilt} probability of chance-constrained set for probabilistic export transport demand satisfaction of order country l from seaport in Turkey i in time period t
 β_{lit} probability of chance-constrained set for probabilistic import transport demand satisfaction of order country l to seaport in Turkey i in time period t
 $De_{ilt}^{exp} \sim N(\mu_{ilt}^{exp}, (\sigma_{ilt}^{exp})^2)$
 $De_{lit}^{imp} \sim N(\mu_{lit}^{imp}, (\sigma_{lit}^{imp})^2)$

Fuzzy capacities and lower/upper bounds in marine and railway transports:

- $\widetilde{Cap}_{ij}^{exp}$ transport capacity of a company-owned Ro-Ro vessel per trip of export operation on marine link $(i, j) \notin L_{ij}$
 $\widetilde{Cap}_{ji}^{imp}$ transport capacity of a company-owned Ro-Ro vessel per trip of import operation on marine link $(j, i) \notin L_{ji}$
 $\widetilde{Cap}_{ij^*}^{exp}$ transport capacity of a company-owned Ro-Ro vessel per trip of export operation on marine link $(i, j^*) \notin L_{ij^*}$ by including a main destination seaport $j^* \in \gamma_j$
 $\widetilde{Cap}_{j^*i}^{imp}$ transport capacity of a company-owned Ro-Ro vessel per trip of import operation on marine link $(j^*, i) \notin L_{j^*i}$ by including a main origin seaport $j^* \in \gamma_j$
 $\widetilde{N}_{ijt}^{exp}$ maximum number of export marine trips that can be performed by company-owned Ro-Ro vessels on marine link $(i, j) \notin L_{ij}$ in time period t
 $\widetilde{N}_{jit}^{imp}$ maximum number of import marine trips that can be performed by company-owned Ro-Ro vessels on marine link $(j, i) \notin L_{ji}$ in time period t
 $\widetilde{N}_{ij^*t}^{exp}$ maximum number of export marine trips that can be performed by company-owned Ro-Ro vessels to the main destination seaport in Europe $j^* \in \gamma_j$ in time period t
 $\widetilde{N}_{j^*it}^{imp}$ maximum number of import marine trips that can be performed by company-owned Ro-Ro vessels from the main origin seaport in Europe $j^* \in \gamma_j$ in time period t
 $\widetilde{UB}_{jkt}^{exp}$ maximum number of export block train services on rail line $(j, k) \notin L_{jk}$ and $k \in D_k \cup T_k$ in time period t
 $\widetilde{UB}_{kjt}^{imp}$ maximum number of import block train services on rail line $(k, j) \notin L_{kj}$ and $k \in D_k \cup T_k$ in time period t
 $\widetilde{LB}_{jkt}^{exp}$ lower bounds on the number of export block train services on rail line $(j, k) \notin L_{jk}$ and $k \in D_k \cup T_k$ in time period t
 $\widetilde{LB}_{kjt}^{imp}$ lower bounds on the number of import block train services on rail line $(k, j) \notin L_{kj}$ and $k \in D_k \cup T_k$ in time period t
 $\widetilde{LB}_{ijt}^{exp}$ lower bounds on the utilization rates of company-owned Ro-Ro vessels for export operation on marine link $(i, j) \notin L_{ij}$ in time period t
 $\widetilde{LB}_{jit}^{imp}$ lower bounds on the utilization rates of company-owned Ro-Ro vessels for import operation on marine link $(j, i) \notin L_{ji}$ in time period t

Deterministic transport capacities of block trains:

- Cap_{jk}^{exp} transport capacity of a block train per service of export operation on rail line $(j, k) \notin L_{jk}$ and $k \in D_k$

Appendix A2: Deterministic, stochastic and fuzzy parameters (Cont.)

Cap_{kj}^{imp} transport capacity of a block train per service of import operation on rail line $(k, j) \notin L_{kj}$ and $k \in D_k$

Cap_{jk}^{exp} transport capacity of a block train per service of export operation on rail line $(j, k') \notin L_{jk'}$ by including a transshipment station, $k' \in T_k$

$Cap_{k'j}^{imp}$ transport capacity of a block train per service of import operation on rail line $(k', j) \notin L_{k'j}$ by including a transshipment station, $k' \in T_k$

Other deterministic and fuzzy parameters for truck and trailer fleet size optimization:

Γ the duration (in hrs) of time period t

$\tilde{\varphi}_{lt}$ number of working days at order country l in time period t

$\tilde{\delta}^E$ the percent of time that a European plated truck is available

$\tilde{\delta}^T$ the percent of time that a Turkish plated truck is available

$\tilde{\varepsilon}$ the percent of time that a trailer is available

Deterministic initial truck and trailer inventory levels:

VJ_{j0} number of European plated trucks initially allocated to seaport in Europe $j \in J$

VK_{k0} number of European plated trucks initially allocated to railway station $k \in K$

VL_{l0}^E number of European plated trucks initially allocated to order country $l \in L$

VL_{l0}^T number of Turkish plated trucks initially allocated to order country $l \in L$

VI_{i0}^E number of European plated trucks initially allocated to seaport in Turkey $i \in I$

VI_{i0}^T number of Turkish plated trucks initially allocated to seaport in Turkey $i \in I$

TL_{l0} number of trailers initially allocated to order country $l \in L$

TI_{i0} number of trailers initially allocated to seaport in Turkey $i \in I$

Appendix A3: Decision variables of the proposed fuzzy and stochastic fleet planning model

Different transport services and outsourcing:

- X_{ilt}^{exp} export quantity of TUs shipped by direct road freight transport on road network $(i, l) \in I \cup L$ in period t
- X_{lit}^{imp} import quantity of TUs shipped by direct road freight transport on road network $(l, i) \in L \cup I$ in period t
- Y_{ijlt}^{exp} export quantity of TUs shipped by combined marine and road transport on marine link $(i, j) \in L_{ij} \cup C_{ij} \cup B_{ij}$ and road network $(j, l) \in J \cup L$ in time period t
- Y_{ljit}^{imp} import quantity of TUs shipped by combined marine and road transport on marine link $(j, i) \in L_{ji} \cup C_{ji} \cup B_{ji}$ and road network $(l, j) \in L \cup J$ in time period t
- $Y_{ij^*lt}^{exp}$ export quantity of TUs shipped by combined marine and road transport to the order country $l \in L$ through the main destination seaport in Europe $j^* \in \gamma_j$ in time period t
- $Y_{lj^*it}^{imp}$ import quantity of TUs shipped by combined marine and road transport from the order country $l \in L$ through the main origin seaport in Europe $j^* \in \gamma_j$ in time period t
- $Y_{ij'l't}^{exp}$ export quantity of TUs shipped by combined marine and road transport to the order country $l \in L$ through the transshipment seaport in Europe $j' \in T_j$ in time period t
- $Y_{lj'l't}^{imp}$ import quantity of TUs shipped by combined marine and road transport from the order country $l \in L$ through the transshipment seaport in Europe $j' \in T_j$ in time period t
- Z_{ijklt}^{exp} export quantity of TUs shipped by intermodal transport on marine link $(i, j) \in L_{ij} \cup C_{ij} \cup B_{ij}$ and rail line $(j, k) \in L_{jk} \cup C_{jk} \cup B_{jk}$ and then road network $(k, l) \in K \cup L$ in time period t
- Z_{lkjlt}^{imp} import quantity of TUs shipped by intermodal transport on marine link $(j, i) \in L_{ji} \cup C_{ji} \cup B_{ji}$ and rail line $(k, j) \in L_{kj} \cup C_{kj} \cup B_{kj}$ and then road network $(l, k) \in L \cup K$ in time period t
- $Z_{ij^*klt}^{exp}$ export quantity of TUs shipped by intermodal transport to the order country $l \in L$ through the main destination seaport in Europe $j^* \in \gamma_j$ in time period t
- $Z_{lkj^*it}^{imp}$ import quantity of TUs shipped by intermodal transport from the order country $l \in L$ through the main origin seaport in Europe $j^* \in \gamma_j$ in time period t
- $Z_{ij'l'klt}^{exp}$ export quantity of TUs shipped by intermodal transport to the order country $l \in L$ through the transshipment seaport in Europe $j' \in T_j$ in time period t
- $Z_{lkj'l'it}^{imp}$ import quantity of TUs shipped by intermodal transport from the order country $l \in L$ through the transshipment seaport in Europe $j' \in T_j$ in time period t
- O_{ilt}^{exp} export quantity of TUs via outsourcing option from seaport in Turkey i to order country l in time period t
- O_{lit}^{imp} import quantity of TUs via outsourcing option from order country l to seaport in Turkey i in time period t

Specific marine transport variables:

- MS_{ijt}^{exp} number of trips by company-owned Ro-Ro vessels for export operation on marine link $(i, j) \notin L_{ij}$ in time period t
- MS_{jit}^{imp} number of trips by company-owned Ro-Ro vessels for import operation on marine link $(j, i) \notin L_{ji}$ in time period t
- $MS_{ij^*t}^{exp}$ number of trips by company-owned Ro-Ro vessels for export operation to the main destination seaport in Europe $j^* \in \gamma_j$ in time period t

Appendix A3: Decision variables of the proposed fuzzy and stochastic fleet planning model (Cont.)

$MS_{j^*it}^{imp}$	number of trips by company-owned Ro-Ro vessels for import operation from the main origin seaport in Europe $j^* \in \gamma_j$ in time period t
R_{ijt}^{exp}	export quantity of TUs shipped by company-owned Ro-Ro vessels on marine link $(i, j) \notin L_{ij}$ in period t
R_{jit}^{imp}	import quantity of TUs shipped by company-owned Ro-Ro vessels on marine link $(j, i) \notin L_{ji}$ in period t
$R_{ij^*t}^{exp}$	export quantity of TUs shipped by company-owned Ro-Ro vessels to the main destination seaport in Europe $j^* \in \gamma_j$ in period t
$R_{j^*it}^{imp}$	import quantity of TUs shipped by company-owned Ro-Ro vessels from the main origin seaport in Europe $j^* \in \gamma_j$ in period t
P_{ijt}^{exp}	export quantity of TUs shipped by other logistics service providers' Ro-Ro vessels on marine link $(i, j) \notin C_{ij}$ in time period t
P_{jit}^{imp}	import quantity of TUs shipped by other logistics service providers' Ro-Ro vessels on marine link $(j, i) \notin C_{ji}$ in time period t
U_{ijt}^{exp}	utilization rate of company-owned Ro-Ro vessels for export operation on marine link $(i, j) \notin L_{ij}$ in time period t
U_{jit}^{imp}	utilization rate of company-owned Ro-Ro vessels for import operation on marine link $(j, i) \notin L_{ji}$ in time period t

Specific rail transport variables:

S_{jkt}^{exp}	number of chartered block trains for export operation on rail line $(j, k) \notin L_{jk}$ in time period t
S_{kjt}^{imp}	number of chartered block trains for import operation on rail line $(k, j) \notin L_{kj}$ in time period t
$S_{jk't}^{exp}$	number of chartered block trains for export operation to the transshipment railway station $k' \in T_k$ in time period t
$S_{k'jt}^{imp}$	number of chartered block trains for import operation from the transshipment railway station $k' \in T_k$ in time period t
Pt_{jkt}^{exp}	export quantity of TUs shipped by public train services on rail line $(j, k) \notin C_{jk}$ and $k \notin G_k$ in time period t
Pt_{kjt}^{imp}	import quantity of TUs shipped by public train services on rail line $(k, j) \notin C_{kj}$ and $k \notin G_k$ in time period t
$Pt_{k'k^*t}^{exp}$	export quantity of TUs shipped by public trains on rail line $(k', k^*) \mid k' \in T_k$ and $k^* \in G_k$ in period t
$Pt_{k^*k't}^{imp}$	import quantity of TUs shipped by public trains on rail line $(k^*, k') \mid k^* \in G_k$ and $k' \in T_k$ in period t

Loaded truck positions on road transport network:

V_{jlt}^{exp}	number of loaded positions performed by European plated trucks for export operation on road transport network $(j, l) \in J \cup L$ in time period t
V_{ljt}^{imp}	number of loaded positions performed by European plated trucks for import operation on road transport network $(l, j) \in L \cup J$ in time period t

Appendix A3: Decision variables of the proposed fuzzy and stochastic fleet planning model (Cont.)

V_{klt}^{exp}	number of loaded positions performed by European plated trucks for export operation on road transport network $(k, l) \in K \cup L$ in time period t
V_{lkt}^{imp}	number of loaded positions performed by European plated trucks for import operation on road transport network $(l, k) \in L \cup K$ in time period t
VE_{ilt}^{exp}	number of loaded positions performed by European plated trucks for export operation on road transport network $(i, l) \in I \cup L$ in time period t
VE_{lit}^{imp}	number of loaded positions performed by European plated trucks for import operation on road transport network $(l, i) \in L \cup I$ in time period t
VT_{ilt}^{exp}	number of loaded positions performed by Turkish plated trucks for export operation on road transport network $(i, l) \in I \cup L$ in time period t
VT_{lit}^{imp}	number of loaded positions performed by Turkish plated trucks for import operation on road transport network $(l, i) \in L \cup I$ in time period t

Truck and trailer fleet size and fleet allocation:

VS_{jlt}^{exp}	European plated truck fleet size for export operations on road transport network $(j, l) \in J \cup L$ in time period t
VS_{ljt}^{imp}	European plated truck fleet size for import operations on road transport network $(l, j) \in L \cup J$ in time period t
VS_{klt}^{exp}	European plated truck fleet size for export operations on road transport network $(k, l) \in K \cup L$ in time period t
VS_{lkt}^{imp}	European plated truck fleet size for import operations on road transport network $(l, k) \in L \cup K$ in time period t
EP_{ilt}^{exp}	European plated truck fleet size for export operations on road transport network $(i, l) \in I \cup L$ in time period t
EP_{lit}^{imp}	European plated truck fleet size for import operations on road transport network $(l, i) \in L \cup I$ in time period t
TP_{ilt}^{exp}	Turkish plated truck fleet size for export operations on road transport network $(i, l) \in I \cup L$ in time period t
TP_{lit}^{imp}	Turkish plated truck fleet size for import operations on road transport network $(l, i) \in L \cup I$ in time period t
TS_{ilt}^{exp}	trailer fleet size required by all of the transportation modes for export operations between seaport in Turkey i and order country l in time period t
TS_{lit}^{imp}	trailer fleet size required by all of the transportation modes for import operations between order country l and seaport in Turkey i in time period t

Truck and trailer inventories on the intermodal logistics network:

VJ_{jt}	number of European plated trucks present at the seaport in Europe j in the end of time period t
VK_{kt}	number of European plated trucks present at the railway station k in the end of time period t
VL_{lt}^E	number of European plated trucks present at the order country l in the end of time period t
VL_{lt}^T	number of Turkish plated trucks present at the order country l in the end of time period t
VI_{it}^E	number of European plated trucks present at seaport in Turkey i in the end of time period t
VI_{it}^T	number of Turkish plated trucks present at the seaport in Turkey i in the end of time period t
TL_{lt}	number of trailers present at the order country l in the end of time period t
TI_{it}	number of trailers present at the seaport in Turkey i in the end of time period t

Appendix A3: Decision variables of the proposed fuzzy and stochastic fleet planning model (Cont.)

Internal empty truck and trailer repositioning:

- V_{jlt}^{rep} number of European plated internal empty truck repositions carried on road transport network $(j, l) \in J \cup L$ during time period t
- V_{ljt}^{rep} number of European plated internal empty truck repositions carried on road transport network $(l, j) \in L \cup J$ during time period t
- V_{klt}^{rep} number of European plated internal empty truck repositions carried on road transport network $(k, l) \in K \cup L$ during time period t
- V_{lkt}^{rep} number of European plated internal empty truck repositions carried on road transport network $(l, k) \in L \cup K$ during time period t
- VE_{ilt}^{rep} number of European plated internal empty truck repositions carried on road transport network $(i, l) \in I \cup L$ during time period t
- VE_{lit}^{rep} number of European plated internal empty truck repositions carried on road transport network $(l, i) \in L \cup I$ during time period t
- VT_{ilt}^{rep} number of Turkish plated internal empty truck repositions carried on road transport network $(i, l) \in I \cup L$ during time period t
- VT_{lit}^{rep} number of Turkish plated internal empty truck repositions carried on road transport network $(l, i) \in L \cup I$ during time period t
- TR_{ilt}^{rep} number of internal empty trailer repositions carried on road transport network $(i, l) \in I \cup L$ during time period t
- TR_{lit}^{rep} number of internal empty trailer repositions carried on road transport network $(l, i) \in L \cup I$ during time period t

External empty truck & trailer repositioning:

- VR_{jlt}^{rep} number of European plated external empty truck repositions carried on road transport network $(j, l) \in J \cup L$ in time period t
- VR_{ljt}^{rep} number of European plated external empty truck repositions carried on road transport network $(l, j) \in L \cup J$ in time period t
- VR_{klt}^{rep} number of European plated external empty truck repositions carried on road transport network $(k, l) \in K \cup L$ in time period t
- VR_{lkt}^{rep} number of European plated external empty truck repositions carried on road transport network $(l, k) \in L \cup K$ in time period t
- VRE_{ilt}^{rep} number of European plated external empty truck repositions carried on road transport network $(i, l) \in I \cup L$ in time period t
- VRE_{lit}^{rep} number of European plated external empty truck repositions carried on road transport network $(l, i) \in L \cup I$ in time period t
- VRT_{ilt}^{rep} number of Turkish plated external empty truck repositions carried on road transport network $(i, l) \in I \cup L$ in time period t
- VRT_{lit}^{rep} number of Turkish plated external empty truck repositions carried on road transport network $(l, i) \in L \cup I$ in time period t
- VR_{jkt}^{rep} number of European plated external empty truck repositions carried on road transport network $(j, k) \in J \cup K$ in time period t
- VR_{kjt}^{rep} number of European plated external empty truck repositions carried on road transport network $(k, j) \in K \cup J$ in time period t
- $VR_{jj't}^{rep}$ number of European plated external empty truck repositions carried among the seaports themselves in Europe $j \in J$ and $j' \in J \setminus \{j\}$ in time period t
-

Appendix A3: Decision variables of the proposed fuzzy and stochastic fleet planning model (Cont.)

$VR_{kk't}^{rep}$	number of European plated external empty truck repositions carried among the railway stations themselves in Europe $k \in K$ and $k' \in K \setminus \{k\}$ in time period t
$VR_{ll't}^{rep}$	number of European plated external empty truck repositions carried among the order countries themselves $l \in L$ and $l' \in L \setminus \{l\}$ in time period t
$VR_{ii't}^{rep}$	number of Turkish plated external empty truck repositions carried among the seaports themselves in Turkey $i \in I$ and $i' \in I \setminus \{i\}$ in time period t
$TTR_{ll't}^{rep}$	number of Turkish plated external empty truck repositions with their own empty trailers carried among the order countries themselves $l \in L$ and $l' \in L \setminus \{l\}$ in time period t
$TR_{ll't}^{rep}$	number of external empty trailer repositions performed by European plated trucks among the order countries themselves $l \in L$ and $l' \in L \setminus \{l\}$ in time period t
$TR_{ii't}^{rep}$	number of external empty trailer repositions performed by Turkish plated trucks among the seaports themselves in Turkey $i \in I$ and $i' \in I \setminus \{i\}$ in time period t
XTR_{lit}^{rep}	number of external empty trailer repositions performed by both European and Turkish plated trucks on road transport network $(i, l) \in I \cup L$ in time period t
XTR_{lit}^{rep}	number of external empty trailer repositions performed by both European and Turkish plated trucks on road transport network $(l, i) \in L \cup I$ in time period t

Idle trucks and trailers awaiting at different locations on the logistics network:

IVJ_{jt}	number of European plated idle trucks awaiting at seaport in Europe j in time period t
IVK_{kt}	number of European plated idle trucks awaiting at railway station k in time period t
IVL_{lt}^E	number of European plated idle trucks awaiting at order country l in time period t
IVL_{lt}^T	number of Turkish plated idle trucks awaiting at order country l in time period t
IVI_{it}^E	number of European plated idle trucks awaiting at seaport in Turkey i in time period t
IVL_{it}^T	number of Turkish plated idle trucks awaiting at seaport in Turkey i in time period t
ITl_{it}	number of idle trailers awaiting at seaport in Turkey i in time period t
ITL_{lt}	number of idle trailers awaiting at order country l in time period t

Truck and trailer fleet expansion and reduction decisions:

Pr_{it}^T	purchasing quantity of Turkish plated new trucks at seaport in Turkey i in time period t
Pr_{it}^E	purchasing quantity of European plated new trucks at order country l in time period t
Prt_{it}	purchasing quantity of new trailers at seaport in Turkey i in time period t
Sp_{it}^T	sales quantity of Turkish plated second-hand trucks at seaport in Turkey i in time period t
Sp_{it}^E	sales quantity of European plated second-hand trucks at order country l in time period t
Spt_{it}	sales quantity of second-hand trailers at seaport in Turkey i in time period t
