ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

Yusuf KUVVETLİ

COORDINATED PRODUCTION – INVENTORY – DISTRIBUTION - ROUTING PROBLEM ON CLOSED LOOP SUPPLY CHAIN WITH RECYCLING OPTION

DEPARTMENT OF INDUSTRIAL ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Doctor of Philosophy by the board of jury on 25/04/2016.

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ABSTRACT

PhD THESIS

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In this study, a coordinated production, inventory, distribution and routing problem in a closed loop supply chain is considered. The closed loop supply chain tackled in this study is capable of both recycling and disposal activities. The primary aim of this study is to investigate the performance of coordinated decisionmaking for production, inventory, distribution and routing in a closed loop supply chain. The problem is dealt with both the production-inventory trade-off and distribution-routing plans at each period on both forward and backward flows. The problem is formulated as a mixed integer linear programming model and solved optimally. The case study for a fats oil supply chain is conducted and results are given. According to case study results, the proposed coordinated decision-making reduces operational costs of the overall chain by about ten percent. Furthermore, random test instances are generated for evaluating the mathematical programming model. A comprehensive sensitivity analysis of this model is performed to assess the effect of changing the model parameters' values. Problems under different scenarios (such as changes in number of nodes and periods) are also run to investiagte CPU time and optimum cost . A decomposition heuristic based on a simulated annealing algorithm is proposed for solving large scale instances. Furthermore, a software with a graphical user interface is developed to automate all calculations for all problem sizes. An extensive comparative study is conducted to compare the results of the mathematical programming model, proposed heuristic and the two stage approach solving forward and backward flows of CLSC respectively.

Key Words: Coordinated production-inventory-distribution-routing, closed loop supply chains, mathematical modelling, simulated annealing, heuristics

ÖZ

DOKTORA TEZİ

GERİ KAZANIM OPSİYONLU KAPALI DÖNGÜ TEDARİK ZİNCİRLERİNDE EŞGÜDÜMLÜ ÜRETİM ENVANTER DAĞITIM ROTALAMA PROBLEMİ

Yusuf KUVVETLİ

ÇUKUROVA ÜNİVERSİTESİ
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Bu çalışmada, kapalı döngü tedarik zincirlerinde eşgüdümlü üretim, envanter, dağıtım ve rotalama problemi ele alınmıştır. Ele alınan kapalı döngü tedarik zinciri, geri kazanım ya da imha etme opsiyonlarına sahiptir. Bu çalışmanın ana amacı, kapalı döngü bir tedarik zincirinde üretim, envanter, dağıtım ve rotalama kararlarının koordineli olarak ele alınmasının etkilerini göstermektir. Problem, her bir periyotta hem ileri hem de tersine akıştaki üretim ve envanter etkileşimleri ile dağıtım ve rotalama planlarına karar vermektedir. Problem, karma tamsayılı lineer programlama modeli olarak formüle edilmiş ve optimal olarak çözülmüştür. Yemeklik yağ üreten bir tedarik zincirinden elde edilen veriler vaka analizi olarak kullanılmış ve sonuçlar sunulmuştur. Vaka analizi sonuçlarına göre, kararlar eşgüdümlü olarak verildiğinde, tüm tedarik zincirinin operasyonel maliyetleri yaklaşık yüzde on oranında azalmıştır. Ayrıca, önerilen matematiksel modelin değerlendirilmesinde rastgele test problemleri üretilmiştir. Modele duyarlılık analizi yapılmış ve modeldeki parametre değerlerinin etkisi değerlendirilmiştir. Farklı senaryolar altında (düğüm sayısı ve periyot sayısı gibi) model çalıştırılmış ve CPU süresi ve optimum maliyet değerleri incelenmiştir. Büyük ölçekli problemlerin çözülmesi için tavlama benzetimi tabanlı bir ayrıştırma sezgiseli geliştirilmiştir. Ayrıca, tüm problemler için hesaplamaları yapacak grafik ara yüze sahip bir yazılım geliştirilmiştir. Önerilen modelden elde edilen sonuçlarla önerilen sezgisel ve yeni ürün ve dönen ürün akışlarının sırayla çözüldüğü iki aşamalı yaklaşım sonuçları kıyaslanmıştır.

Anahtar Kelimeler: Eşgüdümlü üretim-envanter-dağıtım-rotalama, kapalı döngü tedarik zincirleri, matematiksel modelleme, tavlama benzetimi, sezgiseller

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CONTENTS **PAGE**

LIST OF TABLES **PAGE**

LIST OF FIGURES **PAGE**

LIST OF ABBREVIATIONS

CLSC	: Closed loop supply chain
RL	: Reverse logistics
SC	: Supply chain
SCM	: Supply chain management
EOL	: End of life product
WEEE	: Waste electric and electronic equipment
PEARL	: Professional electrical apparatus recyclers league
PIDP	: Production inventory distribution problem
PIRP	: Production inventory routing problem
CLSC-PIRP	: Closed loop supply chain coordinated production, inventory, distribution and routing problem
FSP	: Forward sub-problem
BSP	: Backward sub-problem
CPLEX	: The simplex method as implemented in the C programming language
MILP	: Mixed integer linear programming
GA	: Genetic algorithm
SA	: Simulated annealing algorithm
MIP	: Mixed integer programming
GRASP	: General responsibility assignment software patterns (or principles)
GUI	: Graphical user interface
NPhard	: Non-deterministic polynomial-time hard
a.m.	: Ante meridiam
$	: United States dollar
GHz	: Giga hertz
GB	: Giga byte
CPU	: Central processing unit
TL	: Turkish lira
km	: Kilometer

UNIF	: Uniform Distribution
k, K	: Truck index, number of trucks
n, N, N_c	: Node index, number of nodes, number of customer nodes
t, T	: Period index, number of periods
C_k	: Capacity of truck k
B^m, B^r	: Manufacturing capacity, recycling capacity
pur^m_t, pur^r_t	: Purchasing cost, collection cost
$Imin^m_i$, $Imax^m_i$	: Minimum inventory level, maximum inventory level
$Imin^r_i$, $Imax^r_i$	: Minimum inventory level (returned product), maximum inventory level (returned product)
f^k, ctr	: Fixed and variable transportation costs
s^m_t,s^r_t	: Production and recycling preparation costs
h^m, h^r	: Holding costs of new and returned products
l_{ij}, L	: Distance between nodes and maximum tour length
d^m_{it},d^r_{it}	: Demand of new and returned products
α, β	: Production and maximum recycling ratios
p_t	: Production quantity
p_m^t	: Purchased raw material quantity
p_r^t	: Recycled quantity
Y^m_t, Y^r_t	: Production and recycling operation indicator
I^m_{it},I^r_{it}	: Inventory levels of new and returned products
Q^m_{ikt}, Q^r_{ikt}	: Delivery and pick-up amount
X^m_{ijkt}	: Truck load with new product
X^r_{ijkt}	: Truck load with returned product
Z_{ijkt}	: Travelling indicator
U_{kt}	: Truck usage indicator
Cs	: Number of neighbor solutions
gmin	: Global minimum objective value
cmin	: Current minimum objective value
max_iter	: Maximum number of iterations
S_{ab}	: Cost savings amount

1. INTRODUCTION

In recent years, lots of firms produce green products in the context of globalization and global warming. This is due to not only environmental concerns, laws and consumer senses but also profitable ways of managing supply chains. The returned products or materials have a great potential of gaining economic opportunities.

Returned product is a product that can not perform its functions due to some parts and accordingly the entire product fails. This includes (Blumberg, 2004):

i. Products did not function, however, a possibility of being reused or repaired exist.
ii. Products which are out-of-date, or approached the end of leasing life, but still contain a value
iii. Unsold and undesired products that are included on retailer's shelves
iv. Recalled products
v. Pull-and-Replace repair that generates parts which still contain a value.

The concept of the reverse logistics includes the returned product collecting, remanufacturing, recycling or disposal activities. Reverse logistic is defined as "Reverse logistics comprises all activities involved in managing, processing, reducing and disposing of hazardous or non-hazardous waste from production, packaging and use of products, including the processes of reverse distribution." (Steven, 2004)

According to the study by De Brito and Dekker, drivers that force firms to get start to reverse logistics have been categorized into three main headings: economical (direct and indirect), legislation and corporate citizenship (De Brito and Dekker, 2004).

Reverse logistics activities provide some direct or indirect economic benefits. Decreasing input material costs due to usage of recovered materials instead of raw materials are the most significant direct benefit. Melding used plastic materials, collecting and melding metal scraps for steel works or refurbishing used cell phones can be given as examples of this gain. Moreover, consumers prefer green products instead of other products. Therefore, a reverse logistics program can improve customer relationships and corporate image, accordingly protecting market shares. In United States, there are more than 70000 firms that are relevant with remanufacturing (Lund, 1998). Total annual sales derived from remanufacturing operations are over $53 trillion (EPA, 1997). Total annual sales derived from the steel industry, which is the biggest market in US, is about $56 trillion (Lund, 1998). From this point on, reverse logistic has a great economic impact.

The latter driver of reverse logistics is legislations. Most of the countries have legislated environmental laws such as recycling quotas, packaging restrictions and manufacturing collecting responsibilities. In Turkey, the "waste electric and electronic equipment control regulation" has legislated in 2012 (TCŞB, 2012). Figure 1.1 shows recycling targets of nine different types of waste electric and electronic equipment between years 2012-2016. Another example of regulations is the "White and brown goods disposal" in Netherlands. In this regulation, producers and suppliers are responsible for the disposal of their products (Bressers et al., 2002).

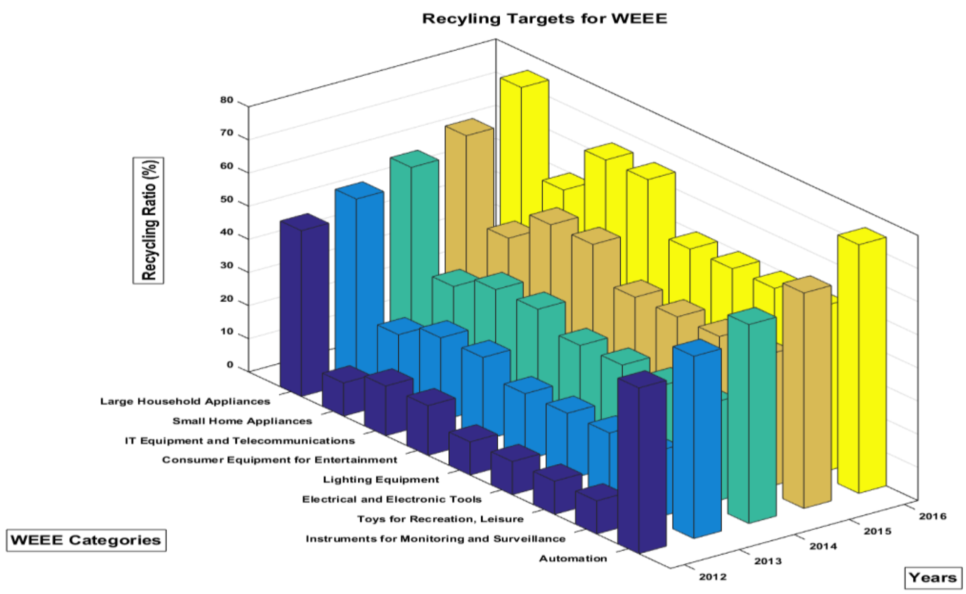


Figure 1.1. Waste electric and electronic equipment (WEEE) recycling targets for years (TCŞB, 2012)

The last driver of reverse logistics is referred to corporate citizenship. Corporate citizenship can be stated as the forces which require companies to be responsible for the environment. In order to keep the environment unpolluted, companies should be responsible for the recycling or suitable disposal of their products. Usually companies take place in programs such as recycling and recovery and keep their alertness toward their clients likewise (Reddy, 2011). For example, Arçelik, Turkish white goods company, runs a campaign that transfers old goods to A+ energy level ones (Arcelik, 2016). Similar initiatives have been taken by other firms.

As regards to drivers of reverse logistics that were mentioned before, several companies use a reverse logistics program. With using a proper reverse logistic program, they manage the processes of planning flow of point of consumption to the point of origin for regaining the value of materials. Therefore, this activities and supply chain constitute the closed loop supply chains (CLSC).

1.1. Closed Loop Supply Chains

The philosophy of the supply chain is based on planning and managing all processes regarding customer expectations from origin point to consumption point. This can be achieved by information sharing and integration along the chain such as raw materials, in-process inventories and finished goods. Closed loop supply chain can be defined as managing all the processes and information flows entire product life-cycle with reverse logistics operations. There are several definitions that are given in previous studies which are mentioned above.

A closed loop supply chain according to the study by Rogers and Tibben-Lembke is defined as the action of implementing, planning and managing the efficient cost effective flow ranging from raw materials to finished goods and relevant information, starting from the consumption point ending with the origin point in order to achieve a recapturable value or a suitable disposal (Rogers and Tibben-Lembke, 1999).

A similar statement of a closed loop supply chain is defined as dealing with the whole process of distribution and collection of the contraction or removal of junk and trash by the same chain (Blumberg, 2004).

A recent definition of closed loop supply chain is given as: *"the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time"* (Guide Jr and Van Wassenhove, 2009).

1.1.1. Managing Closed Loop Supply Chains

The traditional manufacturing environment associated with the reverse logistics operations is transformed to manufacturing environment which is called "recoverable manufacturing environment". Traditional manufacturing environment is about the forward logistics aspects and the recoverable manufacturing environment is about reverse (backward) logistics. Traditional and recoverable manufacturing environments have some differences according to different factors. They are compared in Table 1.1.

Table 1.1. Differences between traditional and recoverable manufacturing environment adapted from (Guide Jr et al., 2000)

Factors	**Recoverable Manufacturing Environment**	**Traditional Manufacturing Environment**
Environmental focus	Prevent post production waste	Focus on design, manufacturing, and other pre-production
Logistics	Supply-driven flows Forward and reverse flows Uncertain timing and quantity of returns	Demand-driven flows Open forward flow No returns
Production planning and control	Need to balance demand with return Material recovery uncertainty Stochastic routings and processing times Manufacturing components: disassembly, remanufacturing and reassembly	No such need Certainty in planned materials More stable routing and processing times Manufacturing components: fabrication and assembly

Table 1.1. Differences between traditional and recoverable manufacturing environment adapted from (Guide Jr et al., 2000) (continued)

Factors	**Recoverable Manufacturing Environment**	**Traditional Manufacturing Environment**
Forecasting	Both core availability and end-product demand Part requirements must forecast due to uncertain recovery rates	Only end-product demand No parts forecasting needed
Purchasing	Highly uncertain material requirements due to the uncertainty of recovery rates	Deterministic material requirements
Inventory control and management	Must track all material types	Must track work-in process and finished goods
Material types	Cores, parts, remanufactured parts, OEM parts, raw materials, work-in process, finished goods and components	Raw materials, work-in process, finished goods and components

Reverse logistics' planning, forecasting and controlling have more complicated processes since it includes some uncertainties. These complicated characteristics are as the following (Guide, 2000):

- ***Timing and quantity of returns are highly uncertain***: There are several causes of product returns such as technology change, end of life etc. A life of product is not certain for almost all returned products. Therefore, it is hard to predict when and how many cores are to be returned. Due to this problem, production and distribution planning of returned material is harder than new ones.
- ***Return quantities should be balanced with demand:*** Returned materials can be used as different type of operations such as recycling, reusing or remanufacturing. In order to the decrease of the inventory level, all of these operations should be managed well. To avoid the excessive amounts of inventory is needed by firms. Therefore, return quantities should be balanced with product demand. This requirement makes inventory control and management processes difficult.
- ***Return products may need disassembly operations:*** Most of the returned products require disassembly operations before restoring parts in order to be

able to distinguish them from usable parts. Disassembly operations affect production control, scheduling, inventory management and materials resource planning management.

- ***Materials recovered from returned materials are highly uncertain:*** Returned products may be used in a variety of purposes such recycling, reselling or remanufacturing according to their conditions. The condition of the returned product makes uncertain recovery amount. While a collected returned product may be used for remanufacturing, another one may be sold in secondary markets due to its good condition. For this reason, it is very complicated to plan and manage returns. This also complicates pricing and purchasing decisions. Because it is not easy to decide the condition of a returned product, a collected product should be priced according to its condition.
- ***A reverse logistics network is required for collecting end-product, locating take-back centers:*** A reverse logistic network constitutes of a set of decisions namely, when products are collected, how they are collected and transported to the factory and where they are collected. Answers of these questions provide information about the number of collection centers and their locations, transportation methods, using (or not) logistic providers.

Major elements of supply chain performance are based on considering the points where storage, production, and cross-dock facilities exist, and transportation links among them being selected. Correspondingly, logistics network design influences the profitability of a reverse logistics program fundamentally. Companies are required to set up logistics formations that optimize the arising goods flows, to account for maximizing the value recovered from returned products (Fleischmann et al., 2004).

- ***Recovering operations have some matching restrictions on bill of materials***: Some parts have more different component than others. Firms are forced to track this parts' serial numbers. Therefore, returned parts should be matched according to such serial numbers. This makes it even harder for production scheduling, remanufacturing and other processes management.

- ***Remanufacturing operations have variable processing time due to uncertain conditions of returned products:*** As mentioned before, each returned product has different condition. This makes a variable processing time for each returned product. Let's consider the closed loop supply chain which has disassembly and remanufacturing operations of a cell-phone for returned product. Each returned phone has a different condition. For example, while a phone has its screen damaged, another phone has a battery fault. These two phones have different disassembly and remanufacturing times due to their different faults. Another problem on this issue is routing. Return products may need different reverse activities. This makes each returned product has different routes on production stage.

All of these reasons, the reverse production environment has considerably complexer than the traditional production environment. Reverse logistics includes set of uncertainties as mentioned above. This causes harder planning, controlling and forecasting activities. Return time and quantity are not certain for almost returns. In a forward flow, firms package products and sent to customer as standardized. But in backward or reverse flow, returned products may not have package or standard types. Moreover, generally returned products have less quantity than new products on transportation. For this reason, there is not a solution for easy to transport packages (palettes, containers). This makes it hard to recognize items on remanufacturing firm and staff. Besides, this type of transportation increases transportation costs (Karaçay, 2005).

1.1.2. Operations of Closed Loop Supply Chains

A typical closed loop supply chain has two flows; backward and forward flows. Closed loop supply chain structures vary to product types accordingly reverse operations that used in the closed loop supply chain. When a product is returned to the company, there are some different options according to product life cycle stage of the product. Figure 1.2 shows reverse logistics aspects and their product life cycle stages. Reverse operations can be divided into four sub-groups according to product's life and condition. These groups are pre-customer, customer, post-customer, end of life (Lambert and Gupta, 2004).

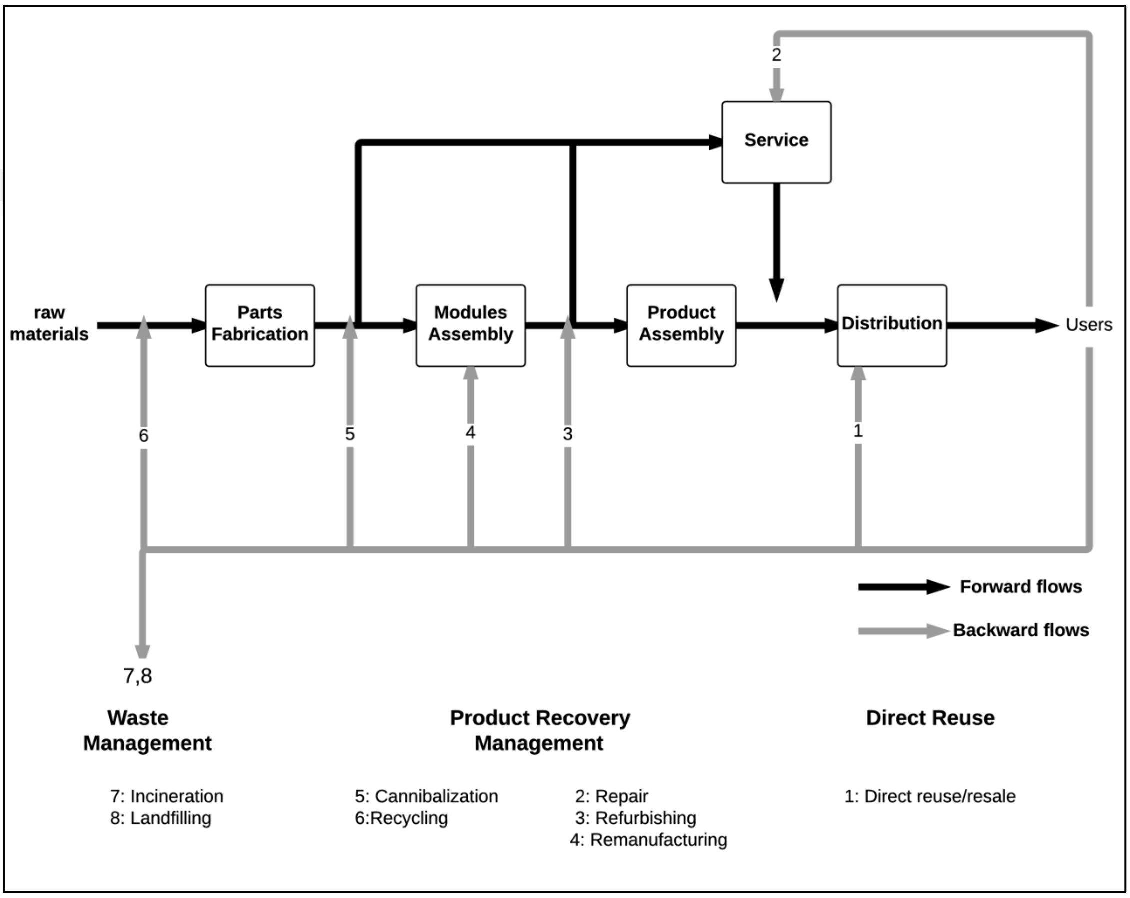


Figure 1.2. Reverse logistics operations (Thierry et al., 1995)

1.1.2.1.Pre-customer phase

This phase includes the operations before product delivery to customer or not used by customer. The main operation of this phase is called *rework*. Rework is an operation that is used for transforming products, which are not suitable for proper usage of customers or does not satisfy the product standards (Lambert and Gupta, 2004).

1.1.2.2.Customer phase

This phase includes the operations which are needed on customer usage of the product. Maintenance and repair can be given as an example of these operations.

Maintenance is stated as a set of functions that are relevant keeping facilities and equipment under suitable working circumstances, and implementing the required repairs incase breakdowns occur, so that the system can function as expected (Stevenson, 2012).

Repair is proposed to recover the product's capability as it breakdowns. Generally it includes component replacement, partial disassembly and reassembly (Lambert and Gupta, 2004).

1.1.2.3.Post-customer phase

This phase includes the operations that are needed to proper collection from customers and some transformations. The operations in this phase are reuse/resale, refurbishing, remanufacturing, recycling and downcycling.

The operation which is needed the least transforms is referred as direct reuse or resale. The firm has many options available according to the following cases; full refund can be selected assuming that the product somehow can be returned to the supplier. However, the product may be sold through an outlet store or may be resold to a different customer, in case the product has not been used. Unless the selling process through either of these options does not meet the requirements, then there is a possibility to sell to a salvage company that will export the product to a foreign market. Reused option is often applied to the returned packaging materials. Obviously, before the reusable totes and pallets are disposed, they will be used many times, while, damaged ones can be refurbished (Rogers and Tibben-Lembke, 1999).

Another way of transforming the products in this phase is refurbishing operations. Refurbishing activities change the returned product like as new product. The processing of an end-of-life product such that its full capability is recovered is included in refurbishing. The outcome is often sold in the second hand market (Lambert and Gupta, 2004).

Remanufacturing is a reverse operation that is used for value-added recovery instead of material recovery such as recycling. Remanufacturing defined as “an industrial process in which worn-out products are restored to like-new condition.” A discarded product is totally disassembled as a consequence of industrial processes sets are handled in a factory environment. Suitable parts are refurbished, cleaned and stored. Then the new product is reassembled from the old one and, where essential, new parts produce a fully corresponding, and sometimes performance and expected lifetime are better compared to the original new product (Lund, 1983). Remanufacturing includes three sub-processes that are given below: (Ilgin and Gupta, 2012)

- Cleaning, inspection, and sorting: Cleaning, examining and sorting (determining the product whether it’s a good condition or not) processes are applied to the end of life products that are collected from customers. When products which have a good condition are disassembled, the others are recycled.
- Disassembly: In this process, products are categorized within their subassemblies and components. Inspection is applied on both disassembled parts and subassemblies. A part or a subassembly is forwarded to facility for recycling or disposal operations directly in case it is not in a good condition. However, some parts or subassemblies that are able to be repaired are processed for repairing. Furthermore, suitable parts and subassemblies are added to the inventory. New parts that are required can be purchased from suppliers and can also be added to the inventory.
- Reassembly: This process is applied to remanufactured products that are stored in the inventory and this is done by using the subassemblies and parts. The resulting product failed while being inspected, these processes such as cleaning and disassembling are implemented again. When the products are functional, then they are wrapped and sent to the returned inventory.

In cannibalization, a part of the returned product is being reused. The aim behind cannibalization is to restore a definite set of reusable parts from returned products. Cannibalized parts are reused in repair, refurbishing, or remanufacturing of other products and components according to the required quality level (Thierry et al., 1995).

Recycling is referred to the process of gathering and processing materials that would be disposed and converting them into new and usable products. Recycling can be beneficial to the community and especially to the environment (EPA, 2016). Recycling has a lot of benefits not only to environment but also to firms as savings. For example, with using recycled materials, waste amounts of products are decreased and it preserves pollutions. It helps creating new jobs for recycling activities. Therefore, it has also some economic benefits.

Downcycling is another application in reverse operations that is used for recycling materials for low-grade aims. For example, cement kilns may be used for filling agent in asphalts on roads (Lambert and Gupta, 2004).

According to report of PEARL, the best way which preserves material, labor and energy resources is to make a brand new product, the second best effective solution is remanufacturing, and recycling is the worst due to resource consumption. Therefore, when a product is collected from the customer, it should be classified properly. This makes collection process too important on closed loop supply chains. The resource preservation percentage of each operation is summarized in Figure 1.3.

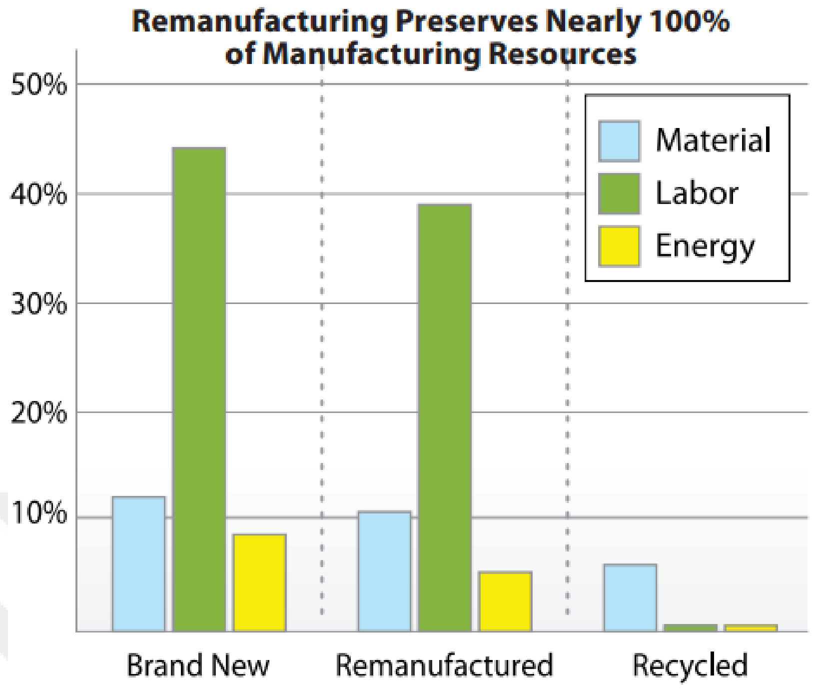


Figure 1.3. Resource usage of different post-customer reverse operations (PEARL, 2010)

1.1.2.4.End of life phase

This phase includes activities on manufacturer responsibilities for proper disposal. If any other way such as remanufacturing or recycling is not suitable for a collected product, firms should be used proper disposal activity to minimize the damage of environment. Incineration and landfilling are the operations of this phase.

Incineration is a process of the oxidation of the combustible materials contained in the returned product. A returned product usually has heterogeneous materials such as organic, metals and water. The aim of incineration is to destroy hazardous materials from product or to reduce its hazard. Incineration processes give a way to restore energy, mineral and/or chemical content from trash (EC, 2006).

If the product has a poor condition and which cannot be reconditioned in any way, the firm will dispose the product for the least cost considering regulations and environmental concern. Any valuable materials will be reclaimed if possible, and any other materials will be removed if they are recyclable before the remainder is finally sent to a landfill (Rogers and Tibben-Lembke, 1999).

The closed loop supply chain structure used in this study is given in Figure 1.4. According to this structure, new products are manufactured on the production facility, and then stored into the warehouse. Customer orders are transported from the warehouse to distributors. Returned products are collected from customers via collectors. Collected products are classified and transferred to the recycler. Plastic or oil products' supply chains can be given as an example to such closed loop supply chain networks.

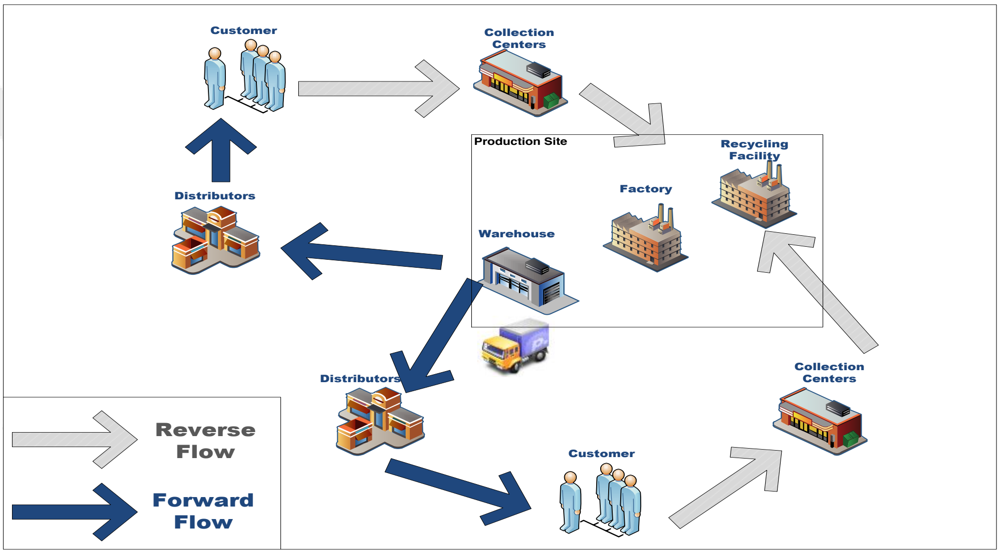


Figure 1.4. Structure of the Closed Loop Supply Chain

1.2. Production and Distribution Models

By increasing integration between production and distribution decisions to supply chains, a more powerful supply chain is provided, additionally overall cost of supply chain will decrease and competiveness will increase. System efficiency is increased by integrated production and distribution models on a supply chain.

Production and distribution models can be divided into three different areas according to the decisions level. The first production and distribution area is strategical, the second is tactical and the last one is operational. All of these decisions are focused on different levels. Figure 1.5 shows the hierarchical approach and problems on each area.

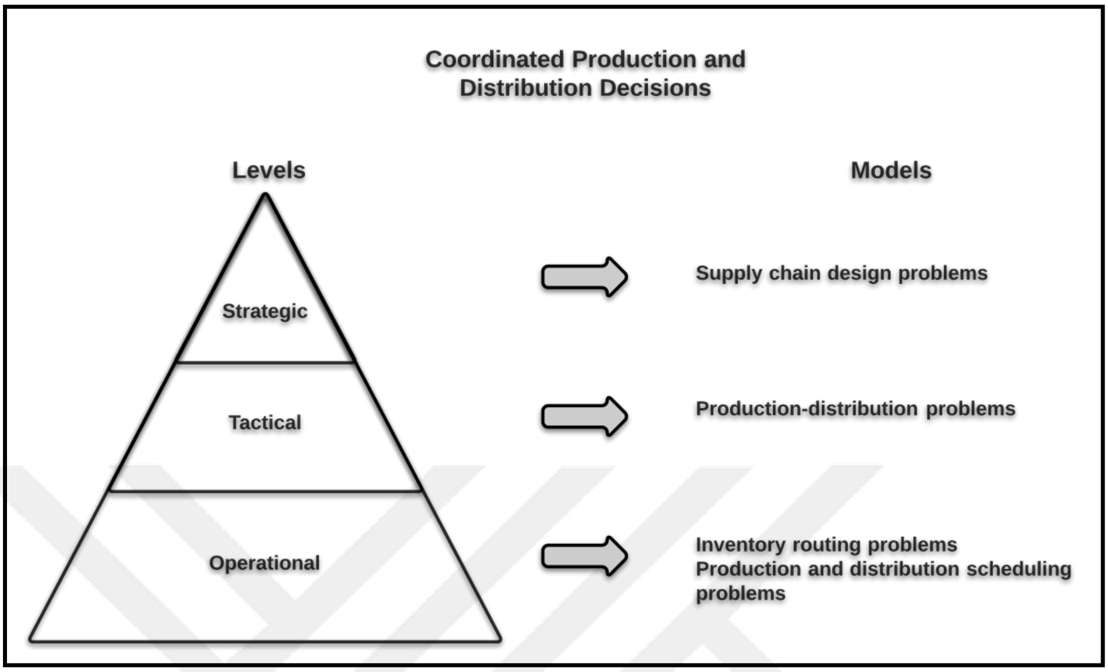


Figure 1.5. Coordinated production and distribution models on different decision levels

1.2.1. Strategic Production and Distribution Models

In the strategic production and distribution models, long-term decisions should be made. The strategic step is highly interested with how the supply chain network is designed (Bilgen and Ozkarahan, 2004). The point of production, storage, and cross-dock facilities, and the option of transportation links among them, are major factors to determine the supply chain performance. Particularly in the perspective of reverse logistics, design of the network is essential for overall chain in order to create profitable reverse logistics systems. A closed loop supply chain must be designed and set up for achieving goods flows optimally to maximizing the value recovered from returned products (Fleischmann et al., 2004).

The closed loop supply chain design problem is depicted in Figure 1.6. The figure implies a categorization of the network into two essential parts. First, used products from individual sources are accumulated by a convergent part and then conveyed to some recovery facility. Second, recovery facilities are linked to individual customers purchasing reusable products by a divergent network part. Furthermore, the actual transformation process of converting used products into reusable ones are hosted by the network among the mentioned parts, namely, the test and grade and the reprocessing stages (Fleischmann, 2001).

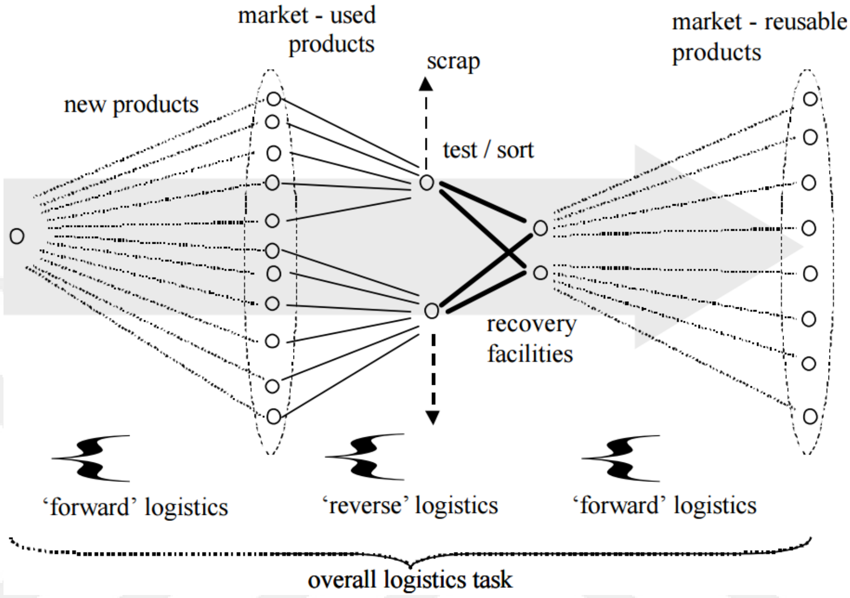


Figure 1.6. Closed Loop Supply Chain Flows (Fleischmann, 2001)

1.2.2. Tactical Production and Distribution Models

The tactical level production and distribution models are concerned with mid-term decisions. Decisions that have from 3 months to 1 year time-horizon mean tactical decisions such as transportation planning, product mix and levels, customer allocation and determining inventory levels in points (Dogan and Goetschalckx, 1999).

Production-distribution problem is a network flow problem that deals with decisions coordinated production and distribution. These decisions are generally taken into account separately by companies. These decisions can be done separately, when distribution decisions have few interactions on the production system and vice-versa. According to this context, the production-distribution problem concerned with assigning products to production lines for minimizing production, holding and transportation costs within linking production and distribution decisions (Dhaenens-Flipo and Finke, 2001).

1.2.3. Operational Production and Distribution Models

Operational level production and distribution models are concerned with short term issues such as scheduling of production, vehicle routes, and short-term inventories. A supply chain can be managed efficiently by balancing truck load with production schedules, decreasing inventory level and deciding minimum cost vehicle routes, therefore integrating production and distribution decisions.

Coordinated production, inventory, distribution and routing problem is to specify the operation schedules to handle the production, inventory, and transportation routing operations according to the customer demand, transporter travel time and capacity limitations, plant production and inventory limitations meet all requirements, while the produced operation cost (i.e., the sum of production, inventory and transportation cost) over a given planning horizon is minimized (Lei et al., 2006).

1.3. Problem Description

In this study, coordinated production and distribution decisions on closed loop supply chains are addressed. Figure 1.7 shows the summary of supply chain flows and given decisions in this problem. In this study, single product, multi-period closed loop supply chain which has single product facility and single recycling facility is considered. Practically, a firm delivers new products while picking up collected products on the same tour. In such distribution, delivery and pick-up processes may sometimes be carried out simultaneously, while one of them is performed. Distribution costs can be reduced by holding new and returned products by the same truck. Moreover, in order to achieve minimum inventory costs, collection or disposal quantities should be balanced by production and recycling quantities.

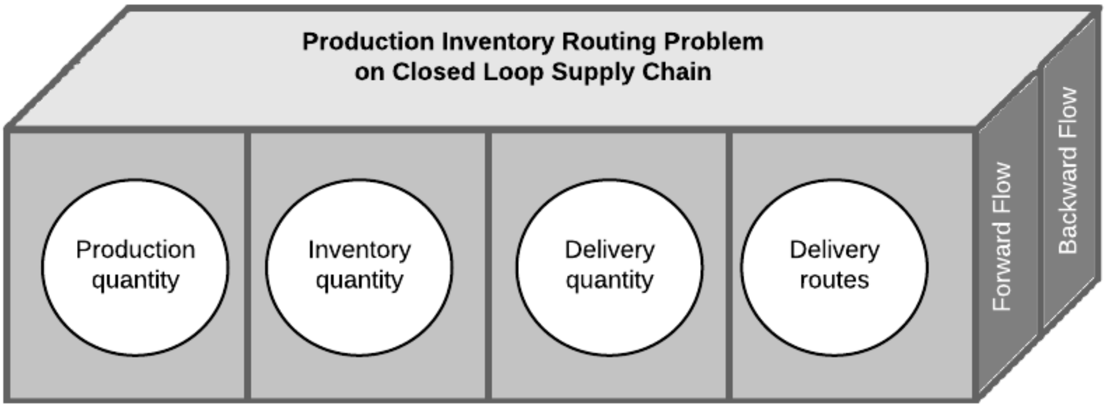


Figure 1.7. Production, inventory, distribution and routing problem on a closed loop supply chain

A good example of the problem can be obtained from fats oil supply chain. Fats and oils production company CLSC can be given as an example of this kind of supply chains. Fats and oil production CLSC has some characteristics as shown above:

- While some of food industries have only one reverse logistics operation (disposal), oil industry has an option to recycle products at a level of raw materials.
- Margarine (general purpose or retail margarines) is collected on these conditions: products that expired shelf life, reologic defects (taste, smell, color, tissue), and process and transportation defects.
- Manufacturers use collected margarines for recycling to decrease production costs.
- After recycling operation, returned fats and oils are purified to reach crude oil specification. Therefore, this emulsion can be used as raw material on manufacturing process. Recycled margarine (emulsion) may be used on new product bill of materials according to regulations, structure and functionality.
- Distribution of margarine is performed by acclimatized trucks. Returned margarines can be transported by the same truck.

1.4. Aim of the Study

Integrated decisions on production and distribution can provide more effective and responsive supply chain. In this study, previous studies are investigated on the area of coordinated production and distribution problems on the operational level. This problem is called as coordinated production, inventory, distribution, and routing problem. Previous studies show that integrated production and distribution decisions decrease the total cost (production, holding, transportation) in finite horizon. In contrast to classical supply chains, a closed loop supply chain has two flows; backward and forward flow. The problem focused on this study is the coordination of not only production and distribution decisions but also forward and backward flows. Table 1.2 shows the decisions and flows on this study.

Table 1.2. Decisions and flow types on managing operational closed loop supply chains

Flow Type \ Decision Type	Production	Distribution
Backward	Coordination between flows and decisions	
Forward		

The main aim of the study is to show the effects of coordination production and distribution decisions on closed loop supply chains. Transportation and inventory cost reductions among all of the closed loop supply chain are provided by taken into account all of these decisions integrally.

Other aims of the study are given below:

- To propose a new mathematical formulation for the problem that mentioned before.
- To develop a heuristic methodology in order to solve large problems.
- To develop a user interface for using proposed methods on real-life applications.
- To conduct a case study that motivated on a food supply chain in order to show usability of the proposed approaches on real-life applications.

1.5. Scope

In this study, coordinated production, inventory, distribution and routing problem is solved for a closed loop supply chain. A mathematical model is proposed for solving this problem. The mathematical model decides on the production-inventory trade-off at each period and distribution-routing plans. A heuristic methodology is proposed for solving large-scale instances. The closed supply chain that is focused in this study has some characteristics:

- A closed loop supply chain is composed by supplier, manufacturer, distributor, customer, recycler and collector.
- A manufacturer and a recycler are in place and production and distribution activities are carried out every day throughout the year.
- Only product recovery option is recycling.
- Raw material based recycling operation is used such as oil and plastic.
- The supply chain has a single product, single manufacturing facility and singe recycling facility.
- It is assumed that the manufacturer and recycler are located in the same location in terms of ease of modelling.

The coordinated production, inventory, distribution and routing problem has the following characteristics:

- The problem is modeled for finite planning horizon.
- Single manufacturer and single recycler are located at a fixed location and a single product is produced.
- In each period, customer demand is required to meet the production environment that has a finite capacity.
- Similarly, recycling facility has a finite capacity

- In order to meet the demand, production at some periods is permitted.
- Production preparation costs occur for each production period. Recycling plant also has similar characteristics.
- Since the amount of returned products depends on the demand size in each demand point, this amount can be estimated as a percentage of new products' demand.
- In order to prevent backorders, keeping inventories at each point is allowed.
- Due to physical conditions, the inventory level of maximum new products and returned products in each point are limited.
- Similarly, the inventory level of minimum new products and returned products in each point are limited for safety stock.
- Distribution activities are carried out by trucks with different capacities and returned products and new products can be transported by the same trucks under capacity constraints.
- The total distance that a truck can travel for a period of time is limited.
- It is intended to employ the minimum number of available trucks. Therefore, the cost of using a truck in a period is considered.
- New products and returned product demands are known throughout the planning horizon.
- It is assumed that trucks travel within constant velocity and for this reason time can be calculated using the distance travelled.

Regarding this issue, truck routes and production quantities are determined optimally when demands are met.

1.6. Original Contributions

Due to the rapid change of the world, academics along with companies should develop supply chains having the ability to deal with coordinated forward and reverse flows of materials. However, initially, they must develop techniques in order to convince managers with the benefits obtained by improving reverse supply chains (Guide et al., 2003).

The production-distribution link within the supply chain has various forms that can take. Products are often manufactured and sent to distributors, retailers or plants. There are many researches and studies which are focused on both production planning and distribution planning. However, efforts trying to model these issues simultaneously are limited. This may be true, due to several explanations. First, various problems regarding these issues are extremely hard to solve independently. This category includes both vehicle routing and machine scheduling. Second, practically, these issues are often distinguished, by inventory buffers. Finally, multiple departments are usually in charge of these two planning activities (Thomas and Griffin, 1996)

In contrast to the efforts spent on both strategic and tactical models, comparably some studies were directed to the functional distribution and production problem. Furthermore, narrow research regarding both vehicle routing decisions and production planning simultaneously, have been made (Bilgen and Ozkarahan, 2004).

Original contributions of the study are given below:

i. The coordinated problem of production, inventory, distribution and routing on closed loop supply chains is investigated.
ii. The effects of coordination production and distribution decisions on closed loop supply chains are demonstrated.
iii. A mixed-integer programming mathematical model is proposed for this problem.
iv. A heuristic approach is proposed for this problem in the case of large-scale instances.
v. Experimental design and range analysis are used by measuring the sensitiveness of the proposed model regarding the values of given parameters.
vi. Scenario analysis is made for investigating the responses of the proposed approach under different conditions.

1.7. Steps and Organization of the Study

1.7.1. Steps

This study has a methodology that has six steps as given follows:

i. Literature Review: The preliminary works on the area of the coordinated production, inventory, distribution and routing problem have explored in this step. Problem formulations and solution methods on previous studies are investigated.

ii. Problem definition: The problem is defined mathematically in this step. Parameters, decision variables and constraints are determined.

iii. Mathematical modelling: In this step, mathematical model is developed for solving the problem. The model is also coded to the suitable mathematical modeling software's language.

iv. Case study: The mixed integer programming model is solved by conducted case study parameters.

v. Two-stage approach modeling: In order to test the proposed method's performance, the two-stage approach which solves the forward and backward sub-problems respectively is considered.

vi. Developing a heuristic method: A heuristic method is proposed for the solution of large-scale instances in this step.

vii. Analysis of results: A computational study (scenario analysis) is built for analyzing the effects of problem parameters when problem has different conditions. Moreover, sensitivity of proposed model is evaluated in this step.

viii. Conclusion: Results of proposed problem and methods are evaluated in this step. Future directions of the study are also given in this step.

1.7.2. Organization

This rest of the study is organized as follows. Section 2 presents the previous studies on the area of coordinated production, inventory, distribution and routing problems. Furthermore, production-distribution studies on closed loop supply chain are summarized in this section. Section 3 shows the materials and methods that used in the study. The mixed-integer mathematical model formulation, proposed heuristic methodology, case study and generating random test instances are declared. Moreover, the graphical user interface which is built for solving proposed problem is given in this section. Section 4 presents computational results for case study and random test instances. In addition to case study results, sensitivity and scenario analysis are conducted. Section 5 summarizes the conclusions of this study. Future suggestions and improvements are also reviewed.

2. LITERATURE REVIEW

The production and distribution decisions are usually made by separately. In production area, lots of studies have examined the production related decisions such as lot-sizing, production scheduling etc. Similarly, preliminary works on distribution area are examined the distribution decisions such as vehicle routing, distribution planning etc.

Coordination between production and distribution decisions in supply chains provides a more powerful supply chain in context of minimizing total cost of SC. Within merging these decisions, firms are able to avoid idle or excessive capacities in terms of both production and transportation. Therefore, the chain can be managed efficiently by coordinating production and distribution decisions.

Both the separated production and distribution decisions have been widely studied; integrated studies about these decisions have been attracted less attention by researchers. As mentioned in Chapter 1, the study's main focus is on operational level coordinated production-distribution decisions. The coordination of production, inventory, distribution and routing problem is about operational decisions regarding supply chains. For this reason, previous works on coordinated production, inventory, distribution and routing problem are discussed in this chapter. Another classification concerning preliminary works is the supply chain type. Therefore, the previous studies that are discussed in this study are evaluated into two groups: operational production and distribution models on SC and production and distribution models on CLSC. Readers who are interested can refer to the review studies (Vidal and Goetschalckx, 1997; Sarmiento and Nagi, 1999; Bilgen and Ozkarahan, 2004) about that concern integrated production and distribution problem for further information.

2.1.Coordinated Production, Inventory and Distribution Planning on Supply Chains

The Coordinated production, inventory, distribution and routing problem is one of the problems concerning supply chains which is focused on the integration of production, inventory and routing decisions on the entire SC. Most of supply chain operational planning studies focus on production or distribution functionalities separately. On the contrary, coordinating production and distribution decisions regarding supply chains have been studied broadly recently.

In one of the preliminary studies, Glover at al.'s published work on the Interfaces journal, the production, distribution and inventory planning is proposed (Glover et al., 1979). They conduct a case study in order to emphasize integrating production and distribution decision. They attempt to solve problems of Agrico Chemical Company. In this study, supply chain is complicated especially when the demands have been shown seasonal characteristic. For this aim, a network model is built for solving integrated production, inventory and distribution problem. The study focuses on both short term and long term problems. In long term planning, location of distribution centers and needed transportation equipment decisions are made. In short term planning, so as to avoid unnecessary production where, when and how much product should be produced and how much of them distributed decisions are made. When considered from this point of view, the study shows that integrating production and distribution decisions are highly practicable and suitable for the real-world applications.

The most important thing is that whether coordinated decisions of production and distributions are beneficial or not. For this aim, Chandra and Fisher's study shows that coordinating production and distribution planning problem can successfully reduce the total production and distribution costs. They modeled two different approaches; coordinated and separated production and distribution problem. They applied both approaches on more than 130 test instances with different conditions. The results shows that coordinated production and distribution decisions are provided to decrease total operation costs between 3-20 percent for different subjects (Chandra and Fisher, 1994). Therefore, this can be concluded from the study, integrated decisions are beneficial and it is the way of transforming efficient supply chain.

Van Buer et al. (1999) studied coordinated production and distribution issues on newspaper industry. They gave a mathematical formulation and built an heuristic search algorithm. In a typical newspaper industry at a metropolitan city; about 1 million newspapers should be produced and distributed before 6 a.m. So firms have only 5-6 hours to produce and distribute the newspapers. This makes the process complicated and firms should coordinate production and distribution planning. Another application of the coordinated production-distribution problem on newspaper industry is proposed by Russel et al. (2008). They propose tabu search procedure and they compare proposed results with a newspaper company routes. It can be saved by using proposed methodology which costs about $ 70,000.

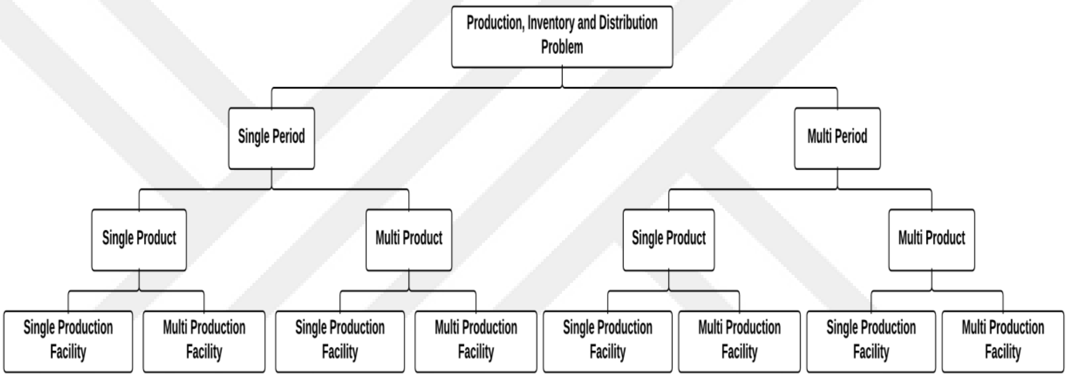


Figure 2.1. Classification scheme of production, inventory and distribution problem

As it is classified on Figure 2.1, previous works on integrated production, inventory and distribution planning on supply chains can be divided into three factors; number of plants, products and periods. Researchers have been given little attention to single period models (Park and Hong, 2009). Moreover, the study focuses on multi-period single product and a single production facility. So that multi-period studies are summarized in this section.

In order to solve single product and single facility PIDP problem, different methodologies have been proposed. Boudia et al. (2007) proposed a GRASP and path relinking algorithm for solving multi-period, single product production-distribution problem. Proposed approaches provide about 15 percent of cost reduction from the classical heuristic approach. In another study of Boudia et al. (2008), they propose two different heuristic approaches for solving single product, single production facility PIRP. Bard and Nananukul solved the problem that has similar characteristics, with using Tabu-search methodology (Bard and Nananukul, 2009a). A branch and price methodology is proposed for solving single product inventory routing problem with production decisions (Bard and Nananukul, 2009b). Genetic and memetic algorithm that are based on heuristic is proposed by Geismar et al. (Geismar et al., 2008). They select a product that has a short shelf life, since no production inventory is permitted and produced materials must be transported directly.

Most of the studies focus on homogenous fleet of vehicles. But practically there are heterogeneous vehicles that have different capacities. A recent study in this area, indicates that two different heterogeneous vehicle types are considered for solving the problem (Toptal et al., 2013). Three solution alternatives called myopic, hierarchical and coordinated are proposed and compared for solving the problem. In another recent study, the problem is studied for a single perishable product (Seyedhosseini and Ghoreyshi, 2014). They consider minimizing total distribution and production costs that include transportation costs from plant to distribution centers, variable production costs and inventory holding costs.

Other heuristic studies for the problem are given as follows: a memetic algorithm (Boudia and Prins, 2009), a branch and price heuristic (Bard and Nananukul, 2010) and adaptive large neighborhood search (Adulyasak et al., 2012).

There are some studies that focused on multi-period, multi-facility type of the problem. This makes it more complicate to solve than the main problem. The production, inventory and distribution problem is handled for single product, multi plant and multi-period SC environment via two-phase solution approach (Lei et al., 2006). They compare the proposed approach with LP results. Moreover, a real supply network is solved by proposed approach and reported.

As mentioned before, the coordinated production-distribution decisions have a great potential for real supply chains. One of the case motivated studies is proposed by Çetinkaya et al. (2009) The multi-product version of the coordinated production and distribution problem is modeled for Frito-Lay Company.

Some of the authors consider multi product, single facility, multi-period production, inventory and distribution problem. In the study of Fumero and

Vercellis, integrated production and distribution model for multi-product, multi-period, one plant and a set of customers are formulated. A decomposition procedure for solving this problem is proposed (Fumero and Vercellis, 1999). Boudia et al. (2006) gives an optimization model for integrated production along with inventory and distribution decisions for multi-period, multi-product supply chain environment. They proposed a Tabu search based on heuristic for solving the problem. The other study focuses on Tabu search whıch is built by Shiguemoto and Armentano (2010). The problem is considered with production capacity constraint and solved by Tabu search and path relinking algorithm (Armentano et al., 2011). The problem handled both single and multi-product environment.

The most sophisticated problem is one comprehending the following characteristics: multi-product, multi-plant, multi-warehouse, multi-customer zone, multi-transport routes and multi-period. A mathematical model is proposed for solving this problem (Dhaenens-Flipo and Finke, 2001). This problem is also considered and solved by genetic algorithms based approach (Fahimnia et al., 2012). Tree-based chromosome representation is applied in the genetic algorithm. A real case study is conducted in this research.

Some of papers focus on scheduling and distribution issues. Chen and Vairaktarakis proposed integrated scheduling and distribution decisions with single plant, direct shipping and a set of jobs and customers conditions (Chen and Vairaktarakis, 2005).

Kuhn and Liske considered the integrated supply and distribution planning problem which is called as the Economic Lot and Supply Scheduling Problem (Kuhn and Liske, 2011). This problem is solved via mathematical modeling and ε-exact solution methods.

2.2. Coordinated Production and Distribution Models on Closed Loop Supply Chains

Production and distribution models on closed supply chain have been attracted by fewer researchers than supply chains. Similarly concerning supply chains, integrated production and distribution models has a great potential for reducing the costs on closed loop supply chains. In this section, previous studies which are focused on only integrated decisions on production and distribution planning are summarized.

Reverse logistics network design issues are published (Fleischmann et al., 2004). The foregoing study of Salema et al. (2009) is focused on integrating network design and production-distribution planning problems. This problem attempts to determine both strategic and tactical decisions together. The recent study of Salema et al. (2010) presents an integrated model which deals with tactical and strategic level decisions together. They formulated a generic network framework which is suitable for different chain structures. The network structure, flow amounts, storing and manufacturing levels and insufficient number new and returned product volumes are determined in this model.

A mathematical model is developed for the integration of forward and reverse distribution network design, along with the locations of facilities accordingly for end-of-lease computer products that are used by forward and reverse logistics operations. A two-phase heuristic algorithm is considered for solving the problem (Lee and Dong, 2008).

This paper illustrates the management of supply chain that handles forward and reverse logistics model simultaneously including strategic and operational alignments. The proposed model aims to re-define Demand Management Procedures, Order Management Procedures, Manufacturing Management Procedures, Procurement Management Procedures, Distribution Management Procedures, Client Management Procedures, etc. (de la Fuente et al., 2008). In conducted case study the shared processes among forward and reverse chains along with processes that are specific is identified.

A closed-loop supply chain is examined where producers manufacture new products and remanufacture used products. By implementing this, there are some decisions that should be considered, namely, which warehouses should have sorting capabilities , which depot and collection centers should be open and the amount of material that should be transported among each pair of sites (Beamon and Fernandes, 2004).

A two-stage facility location model for the reverse logistics including both remanufacturing, and forward and backward flows should be considered simultaneously. They attempt to locate manufacturing, remanufacturing and intermediate center (Lu and Bostel, 2007).

Kannan et al. proposed a study which aims is to develop a multi echelon, multi period, multi-product closed loop supply chain network model for product returns and the decisions are made based on material procurement, production, distribution, recycling and disposal. The suggested heuristics based genetic algorithm (GA) is implemented as a solution methodology to overcome mixed integer linear programming model (MILP) (Kannan et al., 2010). A multi echelon multi product integrated closed loop supply chain network design and third-party logistic provider selection issue is modeled (Sasikumar and Haq, 2011).

This work proposed an coordinated logistics operational model to integrate the cross-functional product logistics flows and used-product reverse logistics flows in a given green-supply chain (Sheu et al., 2005).

A mixed integer programming (MIP) model defines the entire planning process needed to maximize profit by taking into consideration the set of returned products, the recovery of modules and the correspondence of the product mix at various quality stages with taking with respect to modular product design (Das and Chowdhury, 2012).

Both tactical and operational decisions are considered on some studies. In order to solve this phase of the issue, the work considers a Lagrangian relaxation heuristic for holding the practical size return center location-allocation problem within closed-loop supply chains (Min et al., 2005).

In a recent study, supplier contracting, facility location-allocation, production and distribution decisions are made for a single period, multi-echelon and multi-product closed loop supply chain (Das and Rao Posinasetti, 2015).

Another recent study of Chen et al. (2015) gives a mathematical formulation and two stage genetic algorithm approach for solving multi-echelon, multi-component, single time-period closed loop supply chain model. The model decides where and how many quantities will be shipped and produced. The objective of the model is maximizing the profit which deals with total transportation, facility fixed and processing costs.

2.3.Evaluation of Relevant Studies

Coordinated production and distribution decisions are widely studied on supply chains. However, there are still some areas which has not been attracted by researchers. The aim of the study is to fulfill these gaps.

Separated production and distribution planning may cause increasing firms operational cost, using redundant or excessive capacities on production or distribution. Furthermore, this is not practically used for the real-life planning processes. Therefore, integrated approach for production and distribution decisions have been studied widely since 80s. Previous works on coordinated production and distribution problem are focused on classical supply chains. Distincly from classical supply chains, due to environmental concerns and legal obligations, closed loop supply chains management is become an important role for companies. Firms are responsible for collection, reverse activities or proper disposal activities. Production and distribution decisions on closed loop supply chain are generally made separately on operational level. Therefore, there is a research gap on operational coordinated production and distribution planning in closed loop supply chains.

According to solution approaches, most of the studies used mathematical modeling methods for tackling the PIRP on SC. Mixed-integer programming formulations are studied widely in this area. Similarly, the strategic and tactical design problems are usually modeled as mixed integer programming approach. The PIRP on CLSC need to attraction of authors.

In addition to mathematical modeling approaches, most of the PIRP studies are focused on heuristic approaches. It is hard to solve the PIRP in a reasonable time frame due to the NPhard structure of the problem. Therefore, heuristic approaches are applied to the PIRP. Likewise the PIRP, PIRP on CLSC is hard to solve in a reasonable time; therefore, heuristic approaches can be applied to the problem.

Recent studies show that production and distribution studies on closed loop supply chains are quite popular for researchers. Nevertheless, according to our extensive literature review, modeling integrated production, inventory and routing decisions on both forward and backward channel of a closed loop supply chain has not been studied yet.

3. MATERIAL AND METHOD

3. 1. Material

3.1.1. Case Study

As mentioned in section 1.3, this study is motivated by a closed loop supply chain which has two reverse operations that are recycling and disposal. Plastic and oil supply chains can be given as an example of this type of supply chains. Therefore, in this study, a fats and oil closed loop supply chain is selected in order to apply the proposed methods. Fats and oil production CLSC has the following characteristics:

- While some of food industries have only one reverse logistics operation (disposal), oil industry has an option to recycle products at a level of raw materials.
- Margarine (general purpose or retail margarines) products are collected in the case of these conditions: expired shelf life, reologic defects (taste, smell, color, tissue), and process and transportation defects.
- Manufacturers use collected margarines for recycling in order to decrease production costs.
- After recycling operation, returned fats and oils are purified to reach crude oil specification. Therefore, this emulsion can be used as raw material on manufacturing process. Recycled margarine (emulsion) may be used on new product bill of materials according to regulations, structure and functionality.
- Distribution of margarine is performed by acclimatized trucks. Returned margarines can be transported by the same truck.

In this study, the CLSC have a single product which is margarine and a single manufacturing facility where about 50,000 kilograms per year of margarines are produced with different packaging size.

Producer ensures recycling at the level of raw material by collecting back the margarine products from the distributors. Return characteristics were given above. Recycling process includes melting and decantation operations. After these operations, the recycled oil is called as recycled crude oil. The crude oil and recycled crude oil are mixed with water in emulsion premix tank. Then, cooling and kneading processes are passed and production is completed. After production phase, margarines are stored in the acclimatized warehouse. Finally, they are sent from the warehouse to the customer via acclimatized trucks; correspondingly, margarines are distributed among different points in Turkey.

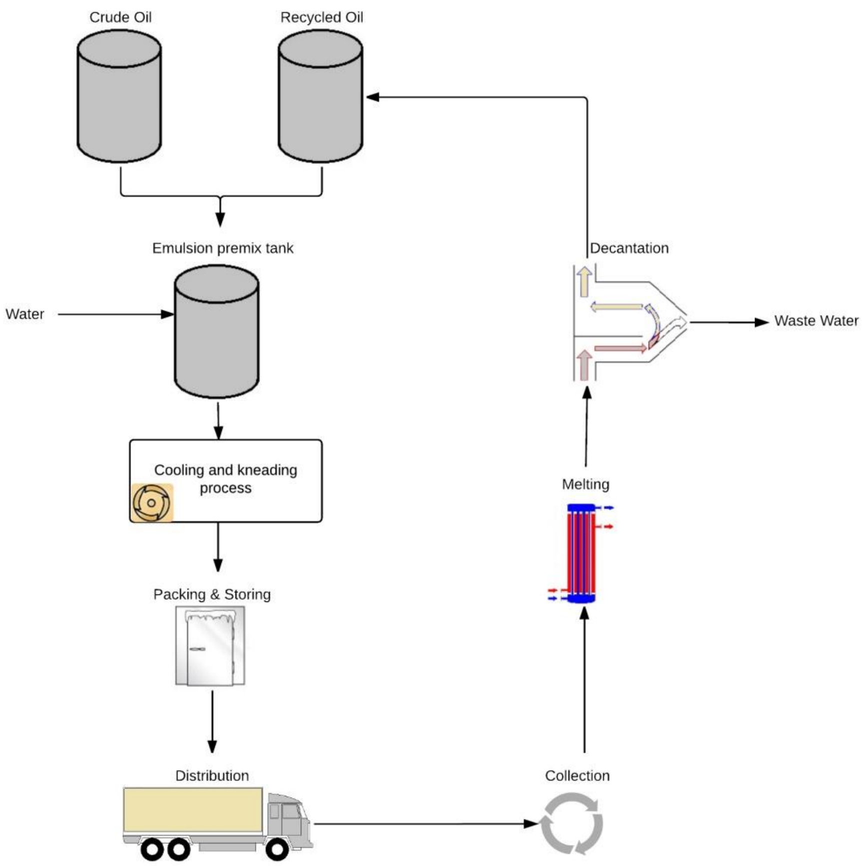


Figure 3.1. Closed loop cycle of margarine product

3.1.2. Random Generated Datasets

There is no real or test instances are published for the proposed problem according to our knowledge. For this reason, in addition to case study randomly generated test instances are used to the problem.

3.2. Method

In this section, CLSC-PIRP and its two sub-problems are explained. CLSC-PIRP is composed of two sub-problems, namely forward and backward sub-problems. Forward and backward flows can be modeled separately, but they have some interactions such as balancing recycled quantities with production quantities and new product distribution in conjunction with returned products distribution. In order to show the effects of solving these sub-problems separately or coordinatedly, sub-problems and CLSC-PIRP are explained in detail, all mathematical formulas regarding the sub problems and the proposed model are given in this section. Additionally, an heuristic methodology for solving large scale problems of the CLSC-PIRP is proposed. In this section, proposed heuristic is also explained.

3.2.1. Closed Loop Supply Chain Coordinated Production-Inventory-Distribution-Routing Problem (CLSC-PIRP)

In a closed loop supply chain, a manufacturer and a recycler are in a place where production and distribution activities are carried out every day throughout the year. New products and returned product demands are known throughout the planning horizon. Since returned products occur based on new product demand of the node in the network, this demand can be modeled as a percentage of new products. The mathematical model determines both the production-inventory trade-off and distribution-routing plans at each period. We called this problem is a closed loop supply chain production, inventory, distribution and routing problem.

Multi-period model of the problem is illustrated in Figure 3.2. According to the figure, in the first period, production and recycling operations are taken place and the new products stored on the warehouse. The first node is visited for new product delivery, other nodes are visited only collecting returned products. One of the nodes is not visited neither new product delivery nor returned product pick-up. In the second period production and recyling operations are also taken place and the new products stored on the warehouse. All of the nodes except the non-visited one are visited for new product delivery. Finally, in the Tth period, production and recycling operations are not taken place. Only two nodes are visited; one for new product delivery, the other for return product collection. In this such system, while production and recycling operations are allowed only some periods, there are not production or recycling operations at some of the periods. Similarly, some of nodes are not visited at some of the periods. The node is visited for new product delivery or returned product collection or both at some of the periods.

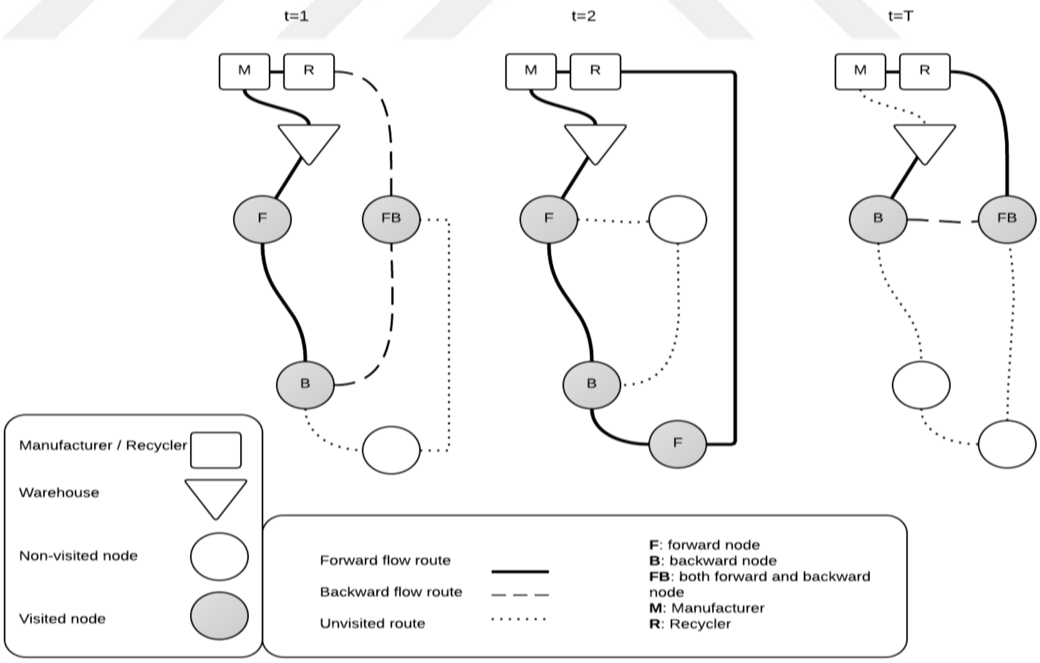


Figure 3.2. Multi-period CLSC-PIRP

3.2.1.1. Objective Function

The objective function of the CLSC-PIRP is to ensure the flow and storage of the products across the supply chain with the minimum total cost. These cost items on the objective function are organized as follows;

- *Production preparation costs:* it arises when production takes place in a period.
- *Recycling preparation costs:* this cost is similar to production preparation costs. If recycling operation takes place in a period, the cost is occurred.
- *Transport and routing costs:* these costs are divided into two categories; fixed and variable. Fixed transportation cost is a cost that occurs if a truck is used in a period. Variable transportation costs are occurred according to the sum of tour lengths.
- *Holding costs (for manufacturers, distributors, collectors):* each node of the network can hold an inventory, keeping these inventories lead to holding costs.
- *Raw material purchase costs:* the amount of raw material used on production lead to purchasing costs.
- *Returned product collection costs:* the collected amount of returned product lead to collection costs. This cost does not depend on recycling, because it is focused on the collection process from the customer to the recycling facility. This cost may occur for loss of prestige or replacing new product instead of returned products. This cost does not include the transportation costs.

Another objective of this problem is to minimize the number of trucks used per period.

3.2.1.2. Constraints

In this problem, some constraints are faced. The constraints can be divided into three sub-groups; 1) inventory, 2) production and 3) distribution and routing. The constraints are given below:

Inventory Constraints

i. *Inventory level should be balanced on production facility:* This constraint is one of the fundamental constraints of production planning. This ensures inventory balances between periods on production facility.

ii. *Returned inventory level should be balanced on recycling facility:* This constraint is similar to inventory balancing constraints. It is used for balancing returned product inventory levels on the recycler with the recycling amounts between periods.

iii. *Inventory level should be balanced on nodes:* This constraint implies inventory level balances between periods for each consumption point.

iv. *Returned inventory level should be balanced on nodes:* This constraint implies returned inventory level balances between periods on each collection point.

v. *Inventory level cannot exceed the limits:* Inventory level at each period on each point must be limited to the minimum and maximum level of inventories.

vi. *Returned inventory level cannot exceed the limits:* Returned inventory level at each period on each point must be limited to the minimum and maximum level of inventories.

Production Constraints

i. *Production capacity cannot be exceeded:* If production takes place on a period, this production quantity must be lower than maximum production capacity.

ii. *Recycling capacity cannot be exceeded:* If recycling takes place on a period, this recycling quantity must be lower than maximum recycling capacity.

iii. *Recycling rate cannot exceed as a certain limit of production rate:* Recycled amount should be lower than multiplying production amount.

iv. *Material used for production and recycling should be balanced by production rate:* This is a case special constraint. This constraint ensures to the production amount is equal to multiplication of used materials (both new and returned quantity) and production rate.

Distribution and Routing Constraints

i. *Truck capacity cannot be exceeded:* A truck has a limited capacity. Therefore, the aim behind this constraint denotes that the load of the truck (both new and returned products) in each point must be lower than the capacity.

ii. *Tour length cannot be exceeded:* Each tour has a length due to time limits. This means each tour must be completed until the period length. This constraint forces that each tour must be completed before the limited tour length.

iii. *Each tour should start and end on the production facility:* All trucks are placed on the production facility; therefore, each tour of a truck must start and end at the production facility.

iv. *Each route must be composed:* This constraint is one of the basic constraints of the vehicle routing problem. A route is consisted of node pairs that represent direct travel between nodes.

3.2.2. Problem Characteristics

The problem is about the coordinating production, inventory, distribution and routing decisions on closed loop supply chains. Regarding this issue, and practically, truck routes and production quantities are determined as optimal when demands are met. The problem's characteristics are given below:

i. The system has a single manufacturer.
ii. The system has a single recycler.
iii. A single product is produced.
iv. The system performs two reverse operations: recycling at the raw material level and disposal.
v. In each period, customer demands are required to be met in the production environment that has a finite capacity.
vi. Production preparation costs occur for each production period.
vii. Recycling plant also has similar characteristics with the production plant.
viii. Distribution activities are carried out by trucks with different capacities.
ix. Returned products and new products can be transported by the same truck under capacity constraints.
x. The total distance that a truck can travel for a period of time is limited.
xi. The problem is intended to employ the minimum number of available trucks. Therefore, the cost of using a truck in a period is considered.
xii. In order to meet the demands, production at some periods is permitted.
xiii. In order to prevent backorders, keeping inventories at each point is allowed.
xiv. Due to physical conditions, the inventory level of maximum new products and returned products in each point is limited.
xv. Similarly, the inventory level of minimum new products and returned products in each point is limited for safety stock.

3.2.3. Assumptions

In modeling phase, there are some facts that are assumed as ease of modeling and problem environment. The problem's assumptions are given below:

i. The problem is focused on a single product. However, similarly the formulation of the problem can be extended to multiple product options.
ii. In this system, there are two reverse logistic operations which are assumed to be applied; recycling and disposal.
iii. It is assumed that the manufacturer and recycler are located in the same location as in practice.
iv. The new product demands within each node and each period are known in advance.
v. The returned amounts at each period and each node are known in advance.
vi. Production and recycling have a limited known capacity in each period.
vii. It is assumed that there is a standard transportation based on volume and weight. This means, all of the goods that are transported have same standard transportation volume and weight.
viii. It is assumed that trucks travel within constant velocity and so time can be computed using the distance travelled.
ix. Trucks of the firms comprise of the fleet that is placed on the facility. Therefore, each tour of a truck must start and end at the production facility.
x. Both recycled and raw materials can be used in production. But recycled materials can only be used as a fraction of total production.
xi. There is a purchasing cost that occurs when raw materials are used in production. Similarly, a collection cost that occurs when returned products are collected.
xii. All the costs are known in advance.

3.2.4. Mathematical Programming Model

In this section, the CLSC-PIRP problem is mathematically modeled. After that, the solution methodologies are investigated for solving this problem.

In this mathematical programming model, the production and distribution plans are determined with minimizing the objective value of the problem while constraints are met. The GAMS model of the CLSC-PIRP is given in Appendix 1.

3.2.4.1. Notation

The notation that is used in this problem is given below. Generally, the "m" means forward flow, in other words it is about new products. Similarly, the "r" means reverse flow, in other words it is about returned products.

Indices

i, j, v — $indices\ for\ nodes, where\ 0\ denotes\ to\ the\ facility, recyler\ and\ warehouse$

k — $index\ for\ vehicles$

t — $index\ for\ periods$

N_c — $set\ of\ consumption\ nodes\ N = N_c \cup \{0\}$

K — $set\ of\ avaliable\ trucks$

T — $set\ of\ periods\ in\ planning\ horizon\ T_0 = T \cup \{0\}$

Parameters

C_k : $Capacity\ of\ vehicle\ k\ (unit)$

$B^{\,m}$: $manufacturing\ capacity\ (unit/period)$

$B^{\,r}$: $recycling\ capacity\ (unit/period)$

q_t^m: $raw\ material\ purchasing\ cost\ on\ period\ t\ (money/unit)$

w_t^r: $EOL\ material\ collection\ cost\ on\ period\ t\ (money/unit)$

g_i^m: $minimun\ inventory\ level\ of\ node\ i\ (unit)$

a_i^m: $maximum\ inventory\ level\ of\ node\ i\ (unit)$

g_i^r: $minimun\ returned\ inventory\ level\ of\ node\ i\ (unit)$

a_i^r: $maximum\ returned\ inventory\ level\ of\ node\ i\ (unit)$

f_k: $fixed\ usage\ cost\ for\ vehicle\ k\ (money/period)$

c : $variable\ cost\ for\ transportation\ (money/distance)$

s_t^m : $production\ preperation\ cost\ on\ period\ t\ (money/period)$

s_t^r : $recycling\ preperation\ cost\ on\ period\ t\ (money/period)$

h^m : $holding\ cost\ for\ new\ product\ (money/(unit * period)$

h^r : $holding\ cost\ for\ returns\ (money/(unit * period))$

l_{ij}: $distance\ between\ (i,j)\ pair\ \ (distance)$

L: $maximum\ tour\ length\ in\ a\ period$

d_{it}^m: $new\ product\ demand\ of\ node\ i\ at\ period\ t\ (unit)$

d_{it}^r: $returned\ product\ demand\ of\ node\ i\ at\ period\ t\ (unit)$

α : $production\ rate$

β : $maximum\ recycling\ ratio$

γ : $multiplier\ for\ calculating\ the\ returned\ product$
$regarding\ recycling\ quantities$

Decision Variables

p_t : $production\ quantity\ at\ period\ t\ (unit)$

p_t^m : $purshased\ raw\ material\ quantity\ at\ period\ t\ (unit)$

p_t^r: $recycling\ quantity\ at\ period\ t\ (unit)$

$Y_t^m: \begin{cases} 1, if\ new\ product\ is\ produced\ at\ period\ t \\ 0, otherwise \end{cases}$

$Y_t^r: \begin{cases} 1, if\ recycling\ operation\ takes\ place\ at\ period\ t \\ 0, otherwise \end{cases}$

I_{it}^m: $Inventory\ level\ on\ node\ i\ at\ period\ t\ (unit)$

I_{it}^r: $Returned\ inventory\ level\ on\ node\ i\ at\ period\ t\ (unit)$

Q_{ikt}^m: $New\ product\ delivery\ amount\ to\ node\ i\ at\ period\ t$
$with\ vehicle\ k\ (unit)$

Q^{r}_{ikt}: *Returned product picked up amount from node i at period t with vehicle k (unit)*

X^{m}_{ijkt}: *New product load on travelling (i, j) pair at period t with vehicle k (unit)*

X^{r}_{ijkt}: *Returned product load on travelling (i, j) pair at period t with vehicle k (unit)*

$$Z_{\mathrm{ijkt}} = \begin{cases} 1, \text{if a delivery made to } (i,j) \text{ pair} \\ \quad \text{at period } t \text{ with vehicle } k \\ \quad 0, \quad \text{otherwise} \end{cases}$$

$$U_{\mathrm{kt}} = \begin{cases} 1, \text{if vehicle } k \text{ is used on period } t \\ \quad 0, \quad \text{otherwise} \end{cases}$$

3.2.4.2. Objective Function

The objective function of production-inventory-distribution-routing problem for integrated reverse logistics network is to ensure the flow and storage of the products across the supply chain with the minimum total cost (3.1.). These cost items on the objective function are organized as follows:

- Production and recycling preparation costs,
- Purchasing and collection costs.
- Transport and routing costs,
- Holding costs (for manufacturers, distributors, collectors).

$$\min z = \sum_{t=1}^{T} s_t^m * Y_t^m + \sum_{t=1}^{T} s_t^r * Y_t^r$$
$$+ \sum_{t=1}^{T} q_t^m * p_t^m + \sum_{t=1}^{T} \left(w_t^r * \sum_{i=0}^{N} \sum_{k=1}^{V} Q_{ikt}^r \right)$$
$$+ \sum_{t=1}^{T} \sum_{k=1}^{K} \mathrm{f}_k * U_{kt} + \sum_{t=1}^{T} \sum_{i=0}^{N} \sum_{\substack{j=0 \\ i \neq j}}^{N} \sum_{k=1}^{V} \mathrm{c} * l_{ij} * Z_{ijkt}$$
$$+ \sum_{t=1}^{T} \sum_{i=0}^{N} h^m * I_{it}^m + \sum_{t=1}^{T} \sum_{i=0}^{N} h^r * I_{it}^r \qquad (3.1.)$$

3.2.4.3. Constraints

In this mathematical model, there are some restrictions that faced in order to find feasible solution for the problem. Therefore, the constraints that faced in the problem are given in equations 3.2-3.23.

$$I_{0t}^m = I_{0t-1}^m + p_t - \sum_{i=1}^{N} \sum_{k=1}^{K} Q_{ikt}^m \qquad \mathrm{t} \in \mathrm{T} \qquad (3.2.)$$

$$I_{0t}^r = I_{0t-1}^r - \gamma * p_t^r + \sum_{i=1}^{N} \sum_{k=1}^{K} Q_{ikt}^r \qquad \mathrm{t} \in \mathrm{T} \qquad (3.3.)$$

$$I_{it}^m = I_{it-1}^m - d_{it}^m + \sum_{k=1}^{K} Q_{ikt}^m \qquad \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{Nc} \qquad (3.4.)$$

$$I_{it}^r = I_{it-1}^r + d_{it}^r - \sum_{k=1}^{K} Q_{ikt}^r \qquad \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{Nc} \qquad (3.5.)$$

Equations 3.2-3.5 are the inventory balancing constraints. New product and returned product inventories are updated using Equations 3.2 and 3.3. In Equations 3.4 and 3.5, it is ensured that the inventories at other nodes are balanced. The amount of inventory at the end of the period in a node is founded by subtracting the demand in that period from the amount at the end of the previous period along with the new products that occur in that period. For returned products, the amount of inventory at the end of the period in a node is founded by adding the collected product in that period to the amount at the end of the previous period and subtracting the total distribution amount of the returned products from this node to other nodes occurring in that period.

$$X_{ijkt}^{m} + X_{ijkt}^{r} \leq C_k * Z_{ijkt} \qquad \mathrm{i} \in \mathrm{N}, \mathrm{j} \in \mathrm{N}, \mathrm{t} \in \mathrm{T}, \mathrm{k} \in \mathrm{K} \qquad (3.6.)$$

Equation 3.6 represents trucks' capacity constraint. It was placed to prevent the truck from exceeding the capacity of the amount of the new and returned products at a point of a period.

$$\sum_{\substack{j=1 \\ i \neq j}}^{N} X_{jikt}^{m} - \sum_{\substack{v=1 \\ i \neq v}}^{N} X_{ivkt}^{m} = Q_{ikt}^{m} \qquad \mathrm{k} \in \mathrm{K}, \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{N} \qquad (3.7.)$$

$$\sum_{k=1}^{K} \sum_{j=1}^{N} X_{0jkt}^{m} - \sum_{k=1}^{K} \sum_{i=1}^{N} X_{i0kt}^{m} = \sum_{k=1}^{K} \sum_{v=0}^{N} Q_{vkt}^{m} \qquad \mathrm{t} \in \mathrm{T} \qquad (3.8.)$$

Equations 3.7 and 3.8 are distribution constraints for the new products. While Equation 3.7 provides incoming-outgoing balance of each point on the distribution, Equation 3.8 ensures balance total flows from the depot to all demand points.

$$\sum_{\substack{j=1 \\ i \neq j}}^{N} X_{jikt}^{r} - \sum_{\substack{v=1 \\ i \neq v}}^{N} X_{ivkt}^{r} = -Q_{ikt}^{r} \qquad \mathrm{k} \in \mathrm{K}, \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{N} \qquad (3.9.)$$

$$\sum_{k=1}^{K} \sum_{j=1}^{N} X_{0jkt}^{r} - \sum_{k=1}^{K} \sum_{i=1}^{N} X_{i0kt}^{r} = \sum_{k=1}^{K} \sum_{v=0}^{N} -Q_{vkt}^{r} \qquad \mathrm{t} \in \mathrm{T} \qquad (3.10.)$$

Equations 3.9 and 3.10 are distribution constraints for the returned products. While Equation 3.9 provides incoming-outgoing balance of each point on the collection, Equation 3.10 ensures balance total flows from the depot to all collection points.

$$\sum_{\substack{j=1 \\ i\neq j}}^{N} Z_{ijkt} - \sum_{\substack{v=1 \\ i\neq v}}^{N} Z_{jvkt} = 0 \qquad k \in K, t \in T, i \in N \qquad (3.11.)$$

$$\sum_{i=0}^{N} \sum_{\substack{j=0 \\ i\neq j}}^{N} Z_{ijkt} * l_{ij} \leq L * U_{kt} \qquad k \in K, t \in T \qquad (3.12.)$$

$$\sum_{i=1}^{N} Z_{0ikt} \geq U_{kt} \qquad k \in K, t \in T \qquad (3.13.)$$

$$\sum_{i=1}^{N} Z_{i0kt} \geq U_{kt} \qquad k \in K, t \in T \qquad (3.14.)$$

Equations 3.11-3.14 represent vehicle routing tour constraints. Equation 3.11 imposes to build tours. Equation 3.12 ensures that tour length cannot exceed a maximum limit of a certain tour in a day. Equations 3.13 and 3.14 impose that each tour must start and end in the depot.

$$p_t \leq B^m * Y_t^m \qquad t \in T \qquad (3.15.)$$

$$p_t^r \leq B^r * Y_t^r \qquad t \in T \qquad (3.16.)$$

$$p_t^r \leq \beta * p_t \qquad t \in T \qquad (3.17.)$$

$$p_t \leq \alpha * (p_t^r + p_t^m) \qquad t \in T \qquad (3.18.)$$

Equations 3.15-3.18 are the constraints that ensure the prevention of exceeding production capacity, determine production and recycling quantities, respectively. Equation 3.15 and 3.16 determine production and recycling quantity within the capacity limits on each production day. Equation 3.17 avoids exceeding recycling quantities to new product quantities' percentage. Equation 3.18 is a special constraint that is used for production environment such as oil supply chain. In order to produce margarine, crude oil is mixed with water; therefore, produced margarine can be calculated to multiply the sum of new and recycled quantities by the production coefficient.

$$g_i^m \leq I_{it}^m \leq a_i^m \qquad \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{N} \qquad (3.19.)$$

$$g_i^r \leq I_{it}^r \leq a_i^r \qquad \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{N} \qquad (3.20.)$$

Equations 3.19 and 3.20 determine a lower and an upper limit for the inventory amounts of the new and returned products in a point of a period. These constraints are necessary because of the problems such as physical space and safety stocks.

$$p_t \geq 0, X_{ijkt}^m \geq 0, Q_{ikt}^m \geq 0, Y_t^m \in \{0,1\} \qquad \mathrm{i} \in \mathrm{N}, \mathrm{j} \in \mathrm{N}, \mathrm{t} \in \mathrm{T}, \mathrm{k} \in \mathrm{K} \qquad (3.21.)$$

$$p_t^r \geq 0, X_{ijkt}^r \geq 0, Q_{ikt}^r \geq 0, Y_t^r \in \{0,1\} \qquad \mathrm{i} \in \mathrm{N}, \mathrm{j} \in \mathrm{N}, \mathrm{t} \in \mathrm{T}, \mathrm{k} \in \mathrm{K} \qquad (3.22.)$$

$$U_{kt} \in \{0,1\}, Z_{ijkt} \in \{0,1\} \qquad \mathrm{i} \in \mathrm{N}, \mathrm{j} \in \mathrm{N}, \mathrm{t} \in \mathrm{T}, \mathrm{k} \in \mathrm{K} \qquad (3.23.)$$

Finally, Equations 3.21-3.23 enforce to define all variables into a valid range. While equation 3.21 is about new product production and distribution decisions, equation 3.22 is used for returned production and distribution decision. In equation 3.23, vehicle routing problems' decision variables are defined and set as binary in order to find the routes and calculate the costs.

3.2.5. Two Stage Approach

Two-stage solution approach implies solving forward and backward sub-problems respectively with separated models. Firstly, the forward sub-problem (FSP) is solved. Thus, distribution days, routes, production days and production quantities of new products are determined. Production plans (p_t) that are optimized on FSP, are used as a parameter on the backward sub-problem. Secondly, the backward sub-problem (BSP) is solved for finding optimal recycling days and quantities that is determined according to the production plan mentioned. Also, distribution days and routes for returned product are found optimally.

3.2.5.1. Forward Sub-problem (FSP)

This stage determines only forward flow of the closed loop supply chain. Therefore, this model determines optimizing new product quantities and new product inventory level of each member at each period, and distribution of quantities and routes for new product distribution at each period.

The objective function of the FSP is to ensure the flow and storage of the new products across the supply chain with the minimum total cost. These cost items on the objective function are organized as follows;

- *Production preparation costs:* this arises when production is taken place in a period.
- *Transport and routing costs:* these costs are divided into two categories; fixed and variable. Fixed transportation cost is a cost that is occurred if a truck is used in a period. Variable transportation costs are occurred according to sum of tour lengths.
- *Holding costs (for manufacturers, distributors):* each node of the network can handle an inventory. Keeping inventories cause holding costs.

Another objective of this problem is minimizing the number of trucks used per period.

In this problem, some constraints are faced. The constraints can be divided into three sub-groups; production, inventory and distribution and routing. The constraints are given below:

Inventory Constraints

i. *Inventory level should be balanced on production facility:* This constraint is one of the fundamental constraints of production planning. This ensures inventory balances between periods on production facility.

ii. *Inventory level should be balanced on nodes:* This constraint implies inventory level balances between periods for each consumption points.

iii. *Inventory level cannot exceed the limits:* Inventory level at each period on each point must be limited into the minimum and maximum level of inventories.

Production Constraints

iv. *Production capacity cannot exceed:* If production takes place on a period, this production quantity must be lower than maximum production capacity.

Distribution and Routing Constraints

v. *Truck capacity cannot exceed:* A truck has a limited capacity. Therefore, this constraint aims in each point that the load of the truck must be lower than the capacity.

vi. *Tour length cannot exceed:* Each tour has a length due to time limits. This means each tour must be completed until the period length. This constraint forces the completions of each tour up to the limited tour length.

vii. *Each tour should start and end on the production facility:* All trucks placed on the production facility. Therefore, each tour of a truck must start and end the production facility.

viii. *Each route must be composed:* This constraint is one of the basic constraints of the vehicle routing problem. A route is consisted of node pairs that represent direct travel between nodes.

3.2.5.2. Backward Sub-problem (BSP)

This stage states the returning flow of the closed loop supply chain. Therefore, this sub-problem determines optimizing recycling quantities; return product inventory level of each item at each period, collection quantities and routes for returned product collection at each period.

The objective function of the BSP is to ensure the flow and storage of the products across the reverse chain with the minimum total cost. These cost items on the objective function are organized as follows;

- *Recycling preparation costs:* This cost is the recycling preparation costs. This occurs when recycling operation takes place in a period.
- *Transport and routing costs:* these costs are divided into two categories; fixed and variable. Fixed transportation cost is a cost that occurs if a truck is used in a period. Variable transportation costs occur according to sum of tour lengths.
- *Holding costs (for manufacturers, collectors):* each node of the network can handle an inventory. Keeping inventories lead to holding costs.
- *Raw material purchase costs:* the amount of raw material used on production lead to purchasing costs.
- *Returned product collection costs:* the collected amount of returned product lead to collection costs. This cost does not depend on recycling, because this cost is focused on collection process from the customer to the recycling facility.

Another objective of this problem is minimizing the number of trucks used per period.

In this problem, some constraints are faced. The constraints can be divided into three sub-groups; production, inventory and distribution and routing. The constraints are given below:

Inventory Constraints

i. *Returned inventory level should be balanced based on the recycling facility:* This constraint is the balancing constraints. It is used for balancing returned product inventory levels on the recycler with the recycling amounts between periods.

ii. *Returned inventory level should be balanced on nodes:* This constraint implies returned inventory level balances between periods on each collection points.

iii. *Returned inventory level cannot exceed the limits:* Returned inventory level at each period on each point must be limited into the minimum and maximum level of inventories.

Production Constraints

iv. *Recycling capacity cannot exceed:* If recycling takes place on a period, this recycling quantity must be lower than maximum recycling capacity.

v. *Recycling rate cannot exceed as a certain limit of production rate:* Recycled amount should be lower than multiplying production amount.

vi. *Material used for production and recycling should be balanced by production rate:* This is a case special constraint. This constraint ensures to the production amount is equal to multiplication of used materials (both new and returned quantity) and production rate.

Distribution and Routing Constraints

vii. *Truck capacity cannot exceed:* A truck has a limited capacity. Therefore, this constraint aims in each point the load (returned products amounts) of the truck must be lower than the capacity.

viii. *Tour length cannot exceed:* Each tour has a length due to time limits. This means each tour must be completed until the period length. This constraint forces each tour completions until the limited tour length.

ix. *Each tour should start and end on the production facility:* All trucks placed on the production facility. Therefore, each tour of a truck must start and end at the production facility.

x. *Each route must be composed:* This constraint is one of the basic constraints of the vehicle routing problem. A route is consisted of node pairs that represent direct travel between nodes.

3.2.6. Problem Characteristics

3.2.6.1. Forward Sub-problem (FSP) Characteristics

The issue here is to coordinated production, inventory, distribution and routing decisions on the forward flow. Regarding this issue, and practically, truck routes and production quantities are determined as optimal when demands are met. The problem's characteristics are given below:

i. The system has a single manufacturer.

ii. A single product is produced.

iii. In each period, customer demands are required to be met in the production environment that has a finite capacity.

iv. Production preparation costs occur for each production period.

v. Distribution activities are carried out by trucks with different capacities.

vi. The total distance that a truck can travel for a period of time is limited.

vii. The problem is intended to employ the minimum number of available trucks. Therefore, the cost of using a truck in a period is considered.
viii. In order to meet the demands, production at some periods is permitted.
ix. In order to prevent backorders, keeping inventories at each point is allowed.
x. Due to physical conditions, the inventory level of maximum new products in each point is limited.
xi. Similarly, the inventory level of minimum new products in each point is limited for safety stock.

3.2.6.2. Backward Sub-problem (BSP) Characteristics

The problem is about to coordinated production, inventory, distribution and routing decisions on the reverse flow. Regarding this issue, and practically, truck routes and recycled quantities are determined as optimal when demands are met. The problem's characteristics are given below:

i. The system has a single recycler.
ii. A single product is recycled.
iii. The system has only recycling operation and the materials should be recycled according to production schedule.
iv. Recycling preparation costs occur for each production period.
v. Distribution activities are carried out by trucks with different capacities.
vi. The total distance that a truck can travel for a period of time is limited.
vii. The problem is intended to employ the minimum number of available trucks. Therefore, the cost of using a truck in a period is considered.
viii. In order to prevent backorders, keeping inventories at each point is allowed.
ix. Due to physical conditions, the inventory level of maximum returned products in each point is limited.
x. Similarly, the inventory level of minimum returned products in each point is limited for safety stock.

3.2.7. Assumptions

3.2.7.1. Forward Sub-problem (FSP) Assumptions

In modeling phase, there are some facts that are assumed to ease of modeling and problem environment. The problem's assumptions are given below:

i. It is assumed that there is only one manufacturer and one warehouse.
ii. The problem is focused on a single product. However, similarly the formulation of the problem can be extended to multiple product options.
iii. The new product demands that each node and each period are known in advance.
iv. Production has a limited capacity in each period.
v. It is assumed that there is a standard transportation based on volume and weight. This means, all of the goods that are transported have same standard transportation volume and weight.
vi. It is assumed that trucks travel within constant velocity and for this reason time can be calculated using the distance travelled.
vii. Trucks of the firms comprise the fleet that is placed on the facility. Therefore, each tour of a truck must start and end the production facility.
viii. All the costs are known in advance.

3.2.7.2. Backward Sub-problem (BSP) Assumptions

In modeling phase, there are some facts that are assumed to ease of modeling and problem environment. The problem's assumptions are given below:

i. It is assumed that there is only one recycler and one warehouse.
ii. The problem is focused on a single product. However, similarly the formulation of the problem can be extended to multiple product options.
iii. In this system, there are two reverse logistic operations that are assumed to be applied; recycling and disposal.

iv. It is assumed that the manufacturer and recycler are located at the same location.
v. The production plan is known in advance.
vi. The returned amounts of each period and each node are known in advance.
vii. Recycling has a limited capacity in each period.
viii. It is assumed that there is a standard transportation based on volume and weight. This means, all of the goods that are transported have same standard transportation volume and weight.
ix. It is assumed that trucks travel within constant velocity and for this reason time can be calculated using the distance travelled.
x. Trucks of the firms comprise the fleet that is placed on the facility. Therefore, each tour of a truck must start and end at the production facility.
xi. Both recycled and raw materials can be used in production. But recycled materials can only be used as a fraction of total production.
xii. There is a purchasing cost that occurs when raw materials are used in production. Similarly, a collection cost that occurs when returned products are collected.
xiii. All the costs are known in advance.

3.2.8. Mathematical Programming Model

Each separated model is a classical coordinated PIRP. Therefore, similar formulations can be found on previous studies. The multi-product version of the problem is proposed in the Fumero and Verceillas's study (1999). The models differently focus one product and include some additional constraints.

3.2.8.1. Forward Sub-problem (FSP) Mathematical Model

In this section, the mathematical model of the FSP is explained. The notation is mentioned in Section 3.2.4.1. The objective of the FSP is given in Equation 3.24 is to minimize the total costs of the forward chain. According to the equation, total cost includes the terms is given below:

- Production preparation costs,
- Truck usage costs,
- Tour costs,
- Inventory holding costs.

$$\min z = \sum_{t=1}^{T} s_t^m * Y_t^m + \sum_{t=1}^{T}\sum_{k=1}^{K} \mathrm{f}_k * U_{kt}$$
$$+ \sum_{t=1}^{T}\sum_{i=0}^{N}\sum_{\substack{j=0 \\ i\neq j}}^{N}\sum_{k=1}^{V} \mathrm{c} * l_{ij} * Z_{ijkt} + \sum_{t=1}^{T}\sum_{i=0}^{N} h^m * I_{it}^m \qquad (3.24)$$

In this model, there are some restrictions that occur, in order to find feasible solution for the problem. Therefore, the constraints that are encountered in the problem are given in equations 3.25-3.37.

$$I_{0t}^m = I_{0t-1}^m + p_t - \sum_{i=1}^{N}\sum_{k=1}^{K} Q_{ikt}^m \qquad \mathrm{t} \in \mathrm{T} \qquad (3.25.)$$

$$I_{it}^m = I_{it-1}^m - d_{it} + \sum_{k=1}^{K} Q_{ikt}^m \qquad \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{Nc} \qquad (3.26.)$$

New product inventories are updated using Equations 3.25 and 3.26. In Equations 3.25 and 3.26, it is ensured that the inventories at other nodes are balanced. The amount of inventory at the end of the period in a node is founded by subtracting the demand in that period from the amount at the end of the previous period and new products that occur in that period.

$$X_{ijkt}^m \leq C_k * Z_{ijkt} \qquad \mathrm{i} \in \mathrm{N}, \mathrm{j} \in \mathrm{N}, \mathrm{t} \in \mathrm{T}, \mathrm{k} \in \mathrm{K} \qquad (3.27.)$$

Equation 3.27 represents trucks' capacity constraint. It was placed to prevent the truck from exceeding the capacity of the amount of the new products at a point of a period.

$$\sum_{\substack{j=1 \\ i \neq j}}^{N} X_{jikt}^{m} - \sum_{\substack{v=1 \\ i \neq v}}^{N} X_{ivkt}^{m} = Q_{ikt}^{m} \qquad \text{k} \in \text{K}, \text{t} \in \text{T}, \text{i} \in \text{N} \qquad (3.28.)$$

$$\sum_{k=1}^{K} \sum_{j=1}^{N} X_{0jkt}^{m} - \sum_{k=1}^{K} \sum_{i=1}^{N} X_{i0kt}^{m} = \sum_{k=1}^{K} \sum_{v=0}^{N} Q_{vkt}^{m} \qquad \text{t} \in \text{T} \qquad (3.29.)$$

Equations 3.28 and 3.29 are distribution constraints for the new products. While Equation 3.28 provides incoming-outgoing balance of each point on the distribution, Equation 3.29 ensures balance total flows from the depot to all demand points.

$$\sum_{\substack{j=1 \\ i \neq j}}^{N} Z_{ijkt} - \sum_{\substack{v=1 \\ i \neq v}}^{N} Z_{jvkt} = 0 \qquad \text{k} \in \text{K}, \text{t} \in \text{T}, \text{i} \in \text{N} \qquad (3.30.)$$

$$\sum_{i=0}^{N} \sum_{\substack{j=0 \\ i \neq j}}^{N} Z_{ijkt} * l_{ij} \leq L * U_{kt} \qquad \text{k} \in \text{K}, \text{t} \in \text{T} \qquad (3.31.)$$

$$\sum_{i=1}^{N} Z_{0ikt} \geq U_{kt} \qquad \text{k} \in \text{K}, \text{t} \in \text{T} \qquad (3.32.)$$

$$\sum_{i=1}^{N} Z_{i0kt} \geq U_{kt} \qquad \text{k} \in \text{K}, \text{t} \in \text{T} \qquad (3.33.)$$

Equations 3.30-3.33 represent vehicle routing tour constraints. Equation 3.30 imposes to build tours. Equation 3.31 ensures that tour length cannot exceed maximum limit of a certain tour in a day. Equations 3.32 and 3.33 impose that each tour must start and end in the depot.

$$p_t \leq B^{m} * Y_t^{m} \qquad \text{t} \in \text{T} \qquad (3.34.)$$

Equation 3.34 is the constraint that ensures the prevention of exceeding production capacity.

$$g_i^m \leq I_{it}^m \leq a_i^m \qquad \text{t} \in \text{T}, \text{i} \in \text{N} \qquad (3.35.)$$

Equation 3.35 determines a lower and an upper limit for the inventory amounts of the new products in a point of a period. This constraint is necessary because of the problems such as physical space and safety stocks.

$$p_t \geq 0, X_{ijkt}^m \geq 0, Q_{ikt}^m \geq 0, Y_t^m \in \{0,1\} \qquad \text{i} \in \text{N}, \text{j} \in \text{N}, \text{t} \in \text{T}, \text{k} \in \text{K} \qquad (3.36.)$$

$$U_{kt} \in \{0,1\}, Z_{ijkt} \in \{0,1\} \qquad \text{i} \in \text{N}, \text{j} \in \text{N}, \text{t} \in \text{T}, \text{k} \in \text{K} \qquad (3.37.)$$

Finally, Equations 3.36-3.37 enforce to define all variables into a valid range. While equation 3.36 is about to new product production and distribution decisions, vehicle routing problems' decision variables are defined and set as binary in order to find the routes and calculate the costs (3.37).

3.2.8.2. Backward Sub-problem (BSP) Mathematical Model

In this section, the mathematical model of the BSP is explained. The notation of this problem is mentioned in Section 3.2.4.1. In BSP, it is different than the mentioned notation that p_t is used as parameter instead of decision variable and the value of p_t becomes FSP. The objective of the BSP that is given in Equation 3.38 is to minimize the total costs of the backward chain. According to the equation, total cost includes the terms that are given below:

- recycling preparation costs,
- purchasing costs of new products,
- collection costs of returned products,
- truck usage costs,
- tour costs,

- Inventory holding costs.

$$\min z = \sum_{t=1}^{T} s_t^r * Y_t^r + \sum_{t=1}^{T} q_t^m * p_t^m + \sum_{t=1}^{T}\left(w_t^r * \sum_{i=0}^{N}\sum_{k=1}^{V} Q_{ikt}^r\right)$$
$$+ \sum_{t=1}^{T}\sum_{i=0}^{N} h^r * I_{it}^r + \sum_{t=1}^{T}\sum_{k=1}^{K} \mathrm{f}_k * U_{kt}$$
$$+ \sum_{t=1}^{T}\sum_{i=0}^{N}\sum_{\substack{j=0 \\ i\neq j}}^{N}\sum_{k=1}^{V} \mathrm{c} * l_{ij} * Z_{ijkt} \qquad (3.38)$$

In this mathematical model, there are some restrictions that are encountered in order to find feasible solution for the problem. Therefore, the constraints that are encountered in the problem are given in equations 3.39-3.53.

$$I_{0t}^r = I_{0t-1}^r - p_t^r + \sum_{i=1}^{N}\sum_{k=1}^{K} Q_{ikt}^r \qquad \mathrm{t} \in \mathrm{T} \qquad (3.39.)$$

$$I_{it}^r = I_{it-1}^r + d_{it}^r - \sum_{k=1}^{K} Q_{ikt}^r \qquad \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{Nc} \qquad (3.40.)$$

Equations 3.39-3.40 are the inventory balancing constraints. Returned product inventories are updated using Equations 3.39 and 3.40. The amount of returned inventory at the end of the period in a node is founded by adding the collected product in that period to the amount at the end of the previous period and subtracting the total distribution amount of the returned products from this node to other nodes occurring in that period.

$$X_{ijkt}^r \le C_k * Z_{ijkt} \qquad \mathrm{i} \in \mathrm{N}, \mathrm{j} \in \mathrm{N}, \mathrm{t} \in \mathrm{T}, \mathrm{k} \in \mathrm{K} \qquad (3.41.)$$

Equation 3.41 represents trucks' capacity constraint. It was placed to prevent the truck from exceeding the capacity of the amount of the returned products at a point of a period.

$$\sum_{\substack{j=1\\ i\neq j}}^{N} X^{r}_{jikt} - \sum_{\substack{v=1\\ i\neq v}}^{N} X^{r}_{ivkt} = -Q^{r}_{ikt} \qquad \mathrm{k} \in \mathrm{K}, \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{N} \qquad (3.42.)$$

$$\sum_{k=1}^{K}\sum_{j=1}^{N} X^{r}_{0jkt} - \sum_{k=1}^{K}\sum_{i=1}^{N} X^{r}_{i0kt} = \sum_{k=1}^{K}\sum_{v=0}^{N} -Q^{r}_{vkt} \qquad \mathrm{t} \in \mathrm{T} \qquad (3.43.)$$

Equations 3.42 and 3.43 are distribution constraints for the returned products. While Equation 3.42 provides incoming-outgoing balance of each point on the collection, Equation 3.43 ensures balance total flows from the depot to all collection points.

$$\sum_{\substack{j=1\\ i\neq j}}^{N} Z_{ijkt} - \sum_{\substack{v=1\\ i\neq v}}^{N} Z_{jvkt} = 0 \qquad \mathrm{k} \in \mathrm{K}, \mathrm{t} \in \mathrm{T}, \mathrm{i} \in \mathrm{N} \qquad (3.44.)$$

$$\sum_{i=0}^{N}\sum_{\substack{j=0\\ i\neq j}}^{N} Z_{ijkt} * l_{ij} \leq L * U_{kt} \qquad \mathrm{k} \in \mathrm{K}, \mathrm{t} \in \mathrm{T} \qquad (3.45.)$$

$$\sum_{i=1}^{N} Z_{0ikt} \geq U_{kt} \qquad \mathrm{k} \in \mathrm{K}, \mathrm{t} \in \mathrm{T} \qquad (3.46.)$$

$$\sum_{i=1}^{N} Z_{i0kt} \geq U_{kt} \qquad \mathrm{k} \in \mathrm{K}, \mathrm{t} \in \mathrm{T} \qquad (3.47.)$$

Equations 3.44-3.47 represent vehicle routing tour constraints. Equation 3.44 imposes to build tours. Equation 3.45 ensures that tour length cannot exceed maximum limit of a certain tour in a day. Equations 3.46 and 3.47 imply that each tour must start and end in the depot.

$$p^{r}_{t} \leq B^{r} * Y^{r}_{t} \qquad \mathrm{t} \in \mathrm{T} \qquad (3.48.)$$

$$p_t^r \leq \beta * p_t \qquad t \in T \qquad (3.49.)$$

$$p_t \leq \alpha * (p_t^r + p_t^m) \qquad t \in T \qquad (3.50.)$$

Equations 3.48-3.50 are the constraints that ensure the prevention of exceeding recycling capacity and determine production and recycling quantities, respectively. Equation 3.48 determines recycling quantity within the capacity limits on each production day. Equation 3.49 avoids exceeding recycling quantities to new product quantities' percentage. Equation 3.50 is a special constraint that is used for production environment such as oil supply chain. In order to produce margarine, crude oil is mixed with water; therefore, produced margarine can be calculated to multiply the sum of new and recycled quantities by the production coefficient.

$$g_i^r \leq I_{it}^r \leq a_i^r \qquad t \in T, i \in N \qquad (3.51.)$$

Equation 3.51 determines the lower and upper limit for the returned inventory amounts in a point of a period. These constraints are necessary because of the problems such as physical space and safety stocks.

$$p_t^r \geq 0, X_{ijkt}^r \geq 0, Q_{ikt}^r \geq 0, Y_t^r \in \{0,1\} \qquad i \in N, j \in N, t \in T, k \in K \qquad (3.52.)$$

$$U_{kt} \in \{0,1\}, Z_{ijkt} \in \{0,1\} \qquad i \in N, j \in N, t \in T, k \in K \qquad (3.53.)$$

Finally, Equations 3.52-3.53 enforce to define all variables into a valid range. While equation 3.52 is about returned production and distribution decisions, vehicle routing problems' decision variables are defined and set as binary in order to find the routes and calculate the costs (3.53).

3.2.9. Proposed Decomposition Heuristic

As mentioned before, the CLSC-PIRP has two sub-problems; PIRP for forward and backward flows. Therefore, CLSC-PIRP is more complicated problem than the PIRP. This means the CLSC-PIRP may not be solved in a reasonable time limit or it may too much CPU time. Therefore, in order to solve large-scale problems a decomposition heuristic is proposed for solving CLSC-PIRP. The methodology decomposes the problem into two parts; routing and other decisions. Routing decisions are made by simulated annealing approach. Other decisions are made by reduced mathematical model.

3.2.9.1. Outline of the Methodology

The outline of the solution methodology is given in Figure 3.3. In this system, the algorithm starts with an initial solution that is generated randomly. The solution refers to visiting places and days. The encoded solution is briefly described in Section 3.2.9.2. When the solution is generated, the most important thing is to decide whether the solution is feasible or not. If the solution is not feasible, the repair function is called and it makes the solution feasible. After deciding the solution feasibility, the tours should be built. This is needed for determining the routes. The modified savings algorithm is proposed for building the routes.

After the routes are built, production, inventory and distribution quantities decisions are held. The CLSC-PIRP model is modified for calculating these quantities. The model is solved according to build routes. This means that built tours are inserted to mathematical model as a parameters and the model decides regarding these tours. The objective value of the model represents the quality of solution. The modified GAMS model is given in Appendix 2. The only difference between modified model and CLSC-PIRP is that modified model allows negative and excessive inventory level for both new and returned product. But the negative or excessive parts of inventories multiplying a penalty value are added to objective function. The penalty value of each backordered or excessive amount equals to production preparation cost. Because, more or less production should be done repairing the solution. Since the aim of the model is to minimize the total cost, the method try to escape infeasable solutions, and avoids negative or excessive inventory levels.

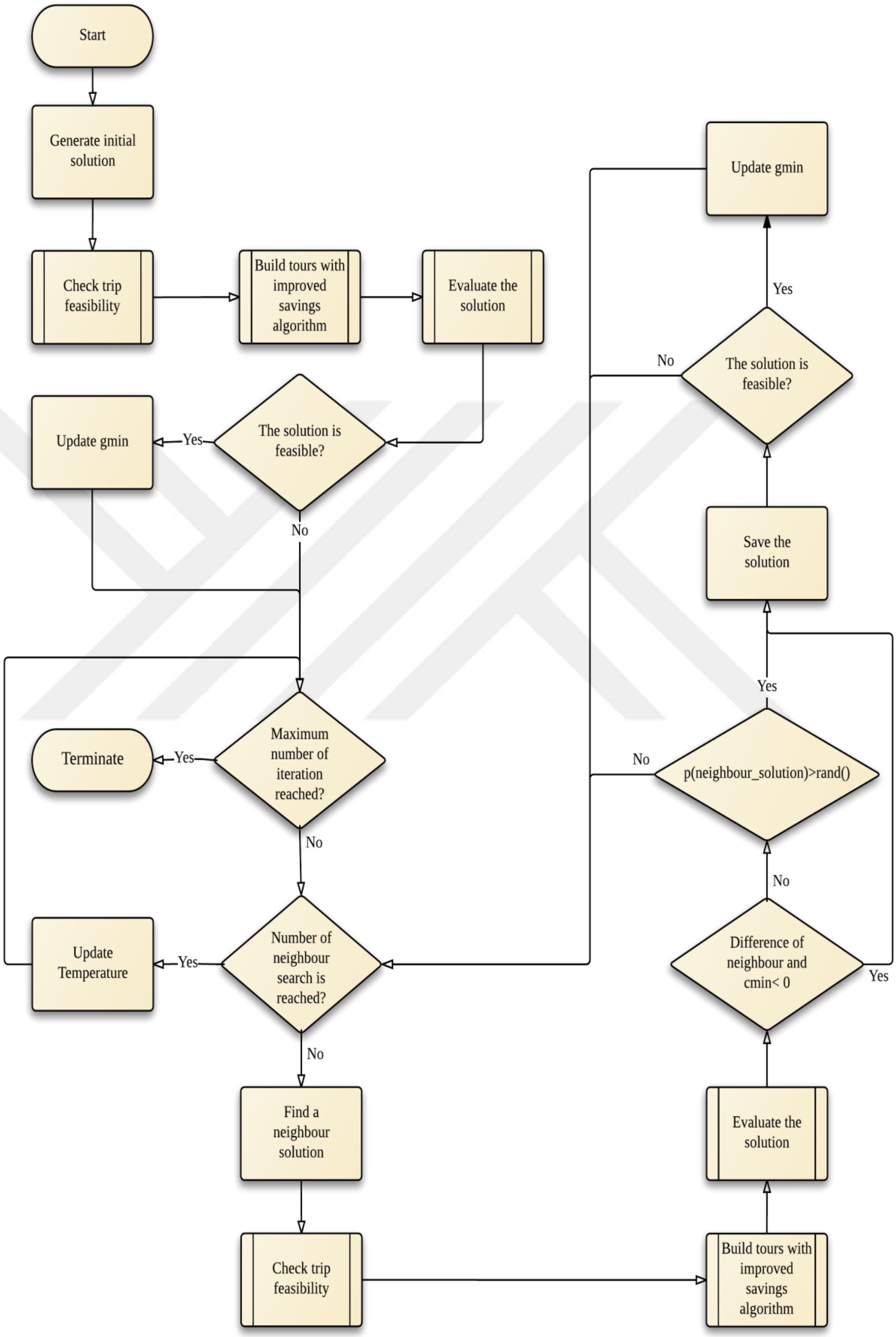


Figure 3.3. Outline of the proposed decomposition method.

When the objective value is calculated, iterations of simulated annealing are started. In each iteration, the number of Cs neighbor solutions are created and evaluated. Similar calculations are done for each neighbor solution. If the objective value of neighbor solution is less than current minimum objective value (cmin), the solution is saved. If the neighbor solution's objective value is more than current minimum fitness value, the probability that is given in equation 3.54 are calculated. If the probability is more than a generated random value between zero and one, the solution is saved. The algorithm is stopped when the maximum number of iteration (max_iter) is reached or the difference between gmin values on the interval of current iteration and 0.1*max-iter is lower than ε=0.00001 value.

This method has a chance to trap into infeasible solutions. Because, all of the built tours guaranteed the routing constraints, however; the production capacities or inventory level constraints may not be satisfied regarding the built tours. Therefore, the solution which has non-penalty amount and lower than global minimum objective value (g_{min}) is selected as new global best solution. If the solution is also feasible, the global best solution is replaced by the solution.

3.2.9.2. Simulated Annealing

Simulated annealing is a random search methodology that is inspired from the physical annealing system. The objective of the problem is represented by the energy level. Desired near-optimal solution of the problem is presented with low energy condition of the physical system. The tricky method that used to reach the solution is statistically modeled the development of the physical system at a sequence of temperatures allowing it to anneal into a level of high condition and too low energy (Kirkpatrick, 1984). Principally, so as to overcome to be stuck in local minimum, this algorithm uses random walk on searching neighbors and accepts some solutions whether there are better or not. This acceptation is done correspondingly by a calculated probability from Boltzmann distribution that is given in equation 3.54 (Chibante et al., 2010).

$$p(x_{new}) = e^{\frac{-(f_{new}-f_{old})}{T}} \quad (3.54.)$$

If the equation is greater than the random number that is generated uniformly between 0 and 1, the worse solution is accepted.

The steps of simulated annealing approach are illustrated on Figure 3.4. The algorithm starts initial parameter decisions. In a simulated annealing there are some parameters that a user must determine. These are given below:

- Initial solution,
- Initial temperature,
- Temperature reduction,
- Number of iterations of Metropolis algorithm,
- Cost function,
- Stopping criteria (Final temperature or maximum number of iteration of the algorithm)

The initial solution is taken randomly from solution space. Beginning of the algorithm user decides the initial temperature, temperature reduction, number of iterations of Metropolis algorithm and stopping criteria.

Initial temperature and temperature reduction parameters provide the acceptation of a worse solution. Temperature must be determined carefully, because it should be large enough for avoiding local minimum and it should be small enough to handle global minimum.

Each solutions energy level is represented with cost function. Cost function is generally the objective of the optimization model.

When the iterations are started, a neighbor solution should be searched. This provides perturbation mechanism for the algorithm. Number of iterations of Metropolis algorithm is referred to how many neighbor solutions should be searched at a specific temperature. In other words, the number of neighbor solutions is sought on each iteration.

Each neighbor solution is evaluated with a cost function value. If the neighbor solution has less cost value (assumed the problem is minimization), the neighbor solution is accepted. If not, it is accepted according to equation 3.54 as mentioned before.

When searching neighbors are finished, the temperature is updated as mentioned cooling of physical annealing process. Many temperature update rules have been proposed by achieving good cooling schedule such as exponential, linear, logarithmic, etc. (Yaghout and Bjarne, 1998).

In this method, solution space is searched stochastically in iterations. Therefore, the search should be stopped when the stopping criteria is met. Stopping criteria can be selected as maximum number of iterations. It is also selected as finishing temperatures are reached.

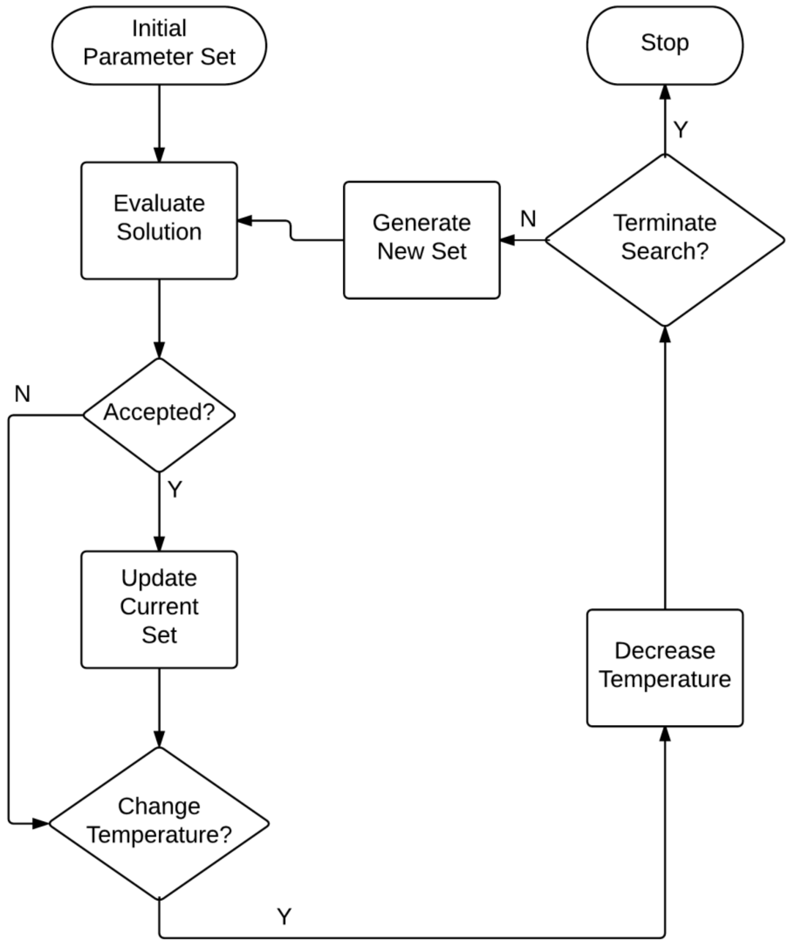


Figure 3.4. Simulated annealing algorithm (Chibante et al., 2010)

3.2.9.3. Solution Encoding

In order to solve CLSC-PIRP, the solution is represented with daily visits of each node. An example solution for five nodes and seven days is shown in Table 3.1. Each cell of the solution can be zero or one. If value of a cell is one, it means this place is visited at a specified day. Similarly, if the value is zero, it means this place is not visited at a specified day. Other production, distribution and routing decisions are computed regarding the visit plan.

Even if the solution that is represented by the matrix given in Table 3.1, actually the solution is described by column vector which transforms the matrix into column vector. It provides to general structure in order to apply population based algorithms such as genetic algorithm etc.

Table 3.1. An example solution representation

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Facility	1	0	1	0	1	1	1
Distributor 1	1	0	1	0	1	0	1
Distributor 2	1	0	0	0	1	0	0
Collector 1	0	0	1	0	1	1	0
Collector 2	0	0	1	0	0	1	1

3.2.9.4. Solution Feasibility

The solution which is encoded as column matrix refers to visit plan each node at each period. But it may be infeasible, due to the reasons as given follows;

- Aggregated truck capacities may not be enough to handle daily loads.
- Any node is visited at a period but the facility is not.

The pseudo codes for the solution checker and repairer function is shown in Table 3.2. This function provides a feasible visiting plan before deciding other variables.

Table 3.2. Pseudo code for solution feasibility checking

```
read the solution vector
transform the vector into solution matrix
set periods to number of solution matrix columns
set nodes to number of solution matrix rows
set current period to one
while current period is not equal to periods
     if sum of total new and returned demands greater than total truck capacity
    select a cell to randomly into the current period column
    set the cell's value to zero
    select another cell to randomly in same row after the current period column
    set the cell's value to one
    endif
    increment current period
set current period to one
while current period is not equal to periods
    if any row except first row greater than zero
        if first row equal to zero
        set first row to one
        endif
    else
        if first row equal to one
        set first row to zero
        endif
    endif
    increment current period
transform the solution matrix to solution vector
output solution vector
```

3.2.9.5. The Modified-Savings Algorithm

A number of trucks for the transportation of the goods each with a specific capacity regarding quantities are available, each one of these trucks that are implemented in the solution, must be included in a route which starts and ends at the depot and visit at least one customer. The aim behind this issue is to decide the customers – routes allocation, the visiting sequence which includes the customers, and vehicle-route allocation (Lysgaard, 1997).

After checking solution's feasibility, the tours must be built due to the need of determining truck routes. A tour should be created based on the visiting plan; therefore, truck routes are built for each period's visited nodes. Tours of each truck in each day a heuristic application which is prosed by Clarke and Wright is implemented. The proposed algorithm called as savings algorithm empowers the quick choice of near-optimal or optimal tours iteratively (Clarke and Wright, 1964).

A number of capacitated trucks considering the demanded goods transportation exists. Each truck that is involved in the solution must have a tour which starts and finishes at the depot and visit at least one customer.

As illustrated in Figure 3.5, the savings method concerns about association nodes that are visited on separate tours. For instance, a and b nodes are visited on different routes. The cost saving (S_{ab}) lead to including them into same tour, are calculated by equation 3.55.

$$S_{ab} = c_{0a} + c_{b0} - c_{ba} \qquad (3.55.)$$

where c_{ab} denotes to trip cost between node a to b. The concept of savings algorithm is based on building tours regarding maximum cost savings.

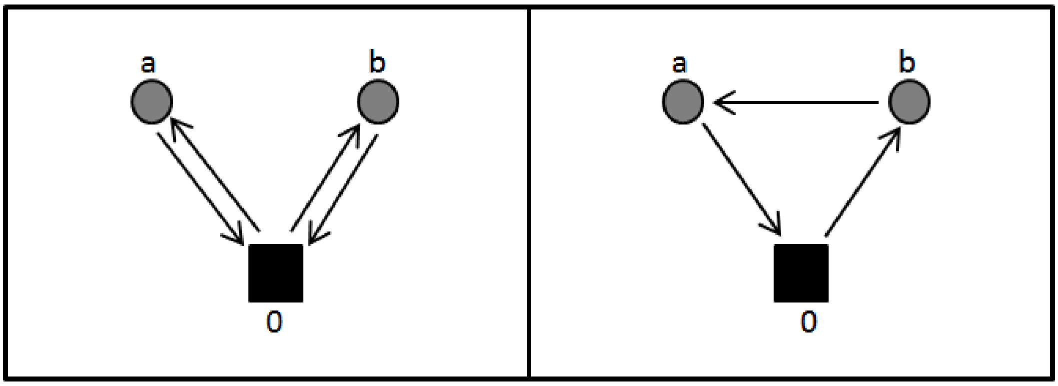


Figure 3.5. The savings method

Classical savings algorithm can be implemented on vehicle routing problem which has both one or more vehicles. However, in the CLSC-PIRP both new and returned products can be transported. Moreover, there is a maximum tour length constraint in the CLSC-PIRP. The steps of modified-savings algorithm are depicted in Figure 3.6. The algorithm starts calculating the savings of each node pairs. Then, the calculated savings are ordered in decreasing. After these calculations, the algorithm iterates until all pairs are revised. When a pair is selected, there are three conditions that can be met:

- Both of the nodes are assigned into a tour,
- One of the nodes are assigned into a tour,
- None of the nodes are assigned into a tour.

If both of the nodes are assigned into a tour, the pair is passed and other most saving node pair is revised. If none of the nodes are assigned into a tour, then new tour is created. If one of the nodes are assigned into a tour, there are two conditions that can be met:

- A new tour is built when the capacity and/or tour constraints are not satisfied.
- A node which is not into any tour is inserted into other node's tour.

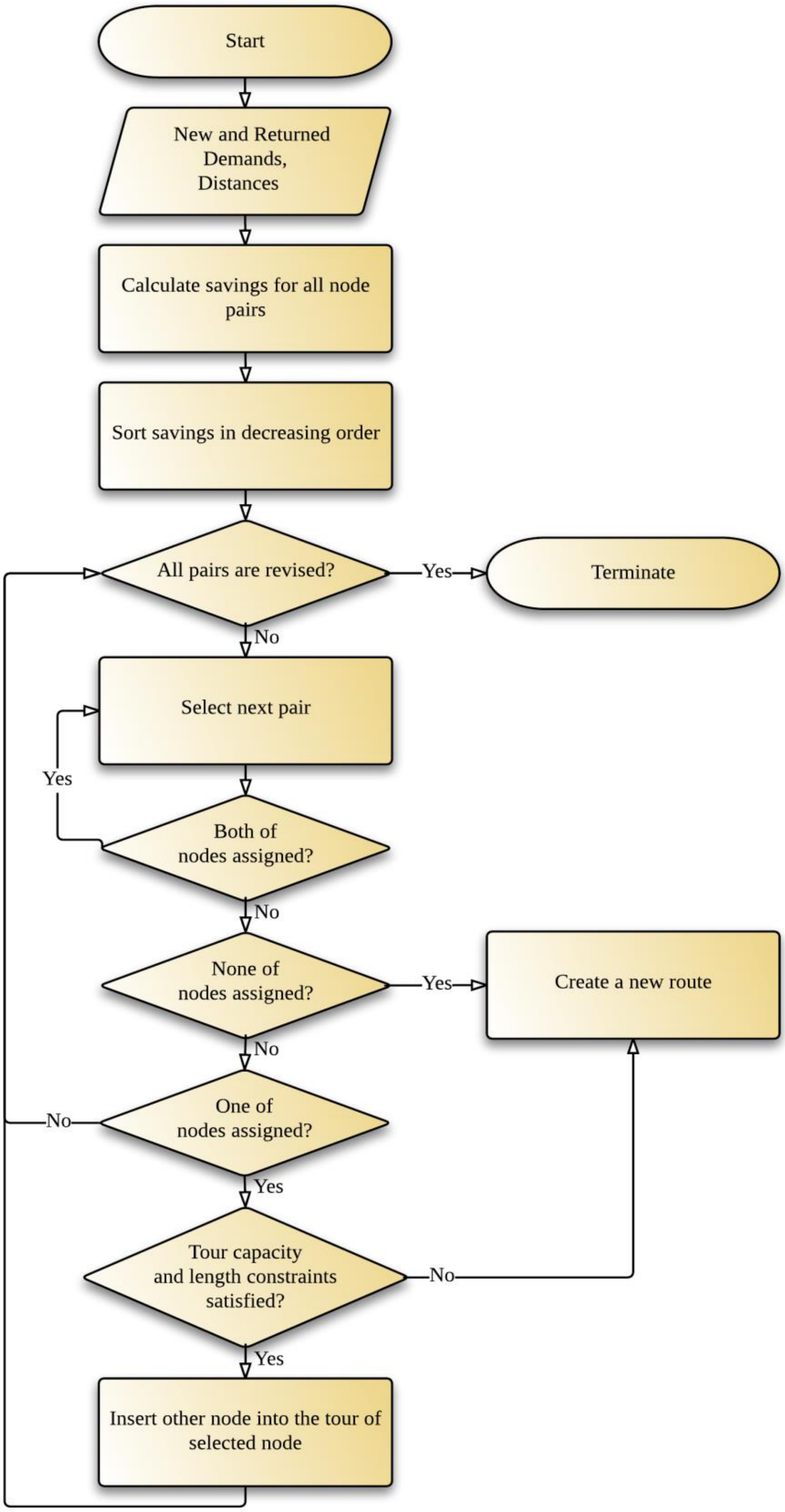


Figure 3.6. Steps of modified savings algorithm

3.2.9.6. Solution Evaluation

The CLSC-PIRP decides production, inventory, distribution and routing variables of both new and returned product, while the proposed heuristic method's solution is visiting plan during the periods of each node. According to these visiting plans, distribution routes of trucks are built by using modified savings algorithm. Another important concern of the proposed heuristic method is to evaluate a solution regarding distribution routes. The proposed mathematical model of the CLSC-PIRP is reduced for evaluating a solution. This reduced mathematical model decides other variables such as production, inventory and distribution regarding given distribution routes.

The objective function of the reduced model is the same with CLSC-PIRP. It is explained in detail in section 3.2.1.1. To mention briefly, the objective function ensures the flow and storage of the products across the supply chain with the minimum total cost. The total cost comprises of production preparation, recycling preparation, holding, purchasing, collection, transport and routing costs.

Differently from the CLSC-PIRP, the number of trucks that is used is determined by the solution and modified-savings algorithm. Therefore, minimizing the number of truck per period is not considered.

In this model, all constraints are the same with CLSC-PIRP. As mentioned before, the constraints can be divided into three sub-groups; production, inventory and distribution and routing.

The main difference between reduced and CLSC-PIRP is decision variables. In the CLSC-PIRP, Z and U are binary decision variables that indicate truck visits and usage conditions per period for each truck. However, in the reduced model, these variables are obtained from the solution and modified-savings algorithm. Therefore, the reduced model has same notations except Z and U. Z and U are modeled as parameters on the reduced model.

In the reduced model, it is assumed that truck routes of each truck and each period are known. The assumptions of the CLSC-PIRP are valid for the reduced model.

All the reduced mathematical model is determined the same with CLSC-PIRP, in order to avoid infeasible solutions. In other words, even if Z and U are selected as parameters on the reduced model, the rest of modeling items such as the objective function and constraints are the same as the CLSC-PIRP. For such approach each solution are checked of feasibility conditions of the solution. If the solution is not feasible, the reduced model becomes infeasible; therefore, the solution evaluation value is assigned to too high number in order to avoid trapping into infeasible solutions.

3.2.10. Closed Loop Supply Chain Production & Distribution Planner Graphical User Interface

The proposed methods have great ability to reducing total operation costs for real life applications. Therefore, in this study a graphical user interface is coded in order to provide comprehensive uses of proposed methods. The graphical user interface is called as closed loop supply chain production & distribution planner is shown in Figure 3.7-3.11.

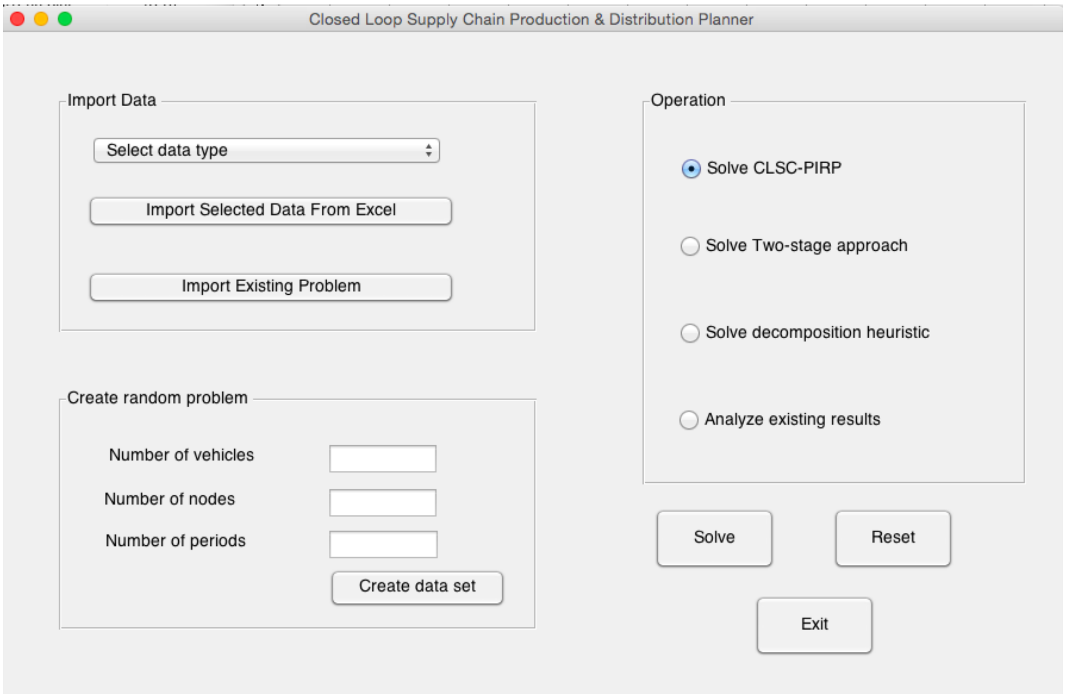


Figure 3.7. Main menu of the GUI

Figure 3.7 is the main menu of proposed software. The main menu consists of three parts. The first part is importing existing problem data. Each parameter can be imported from Microsoft Excel or all parameters can be imported from the workspace. The second part allows creating random problem according to given number of trucks, nodes and periods. The last part is to select the operation that runs. The created problem can be solved by CLSC-PIRP, two-stage approach and the decomposition heuristic. Moreover, a problem that was solved previously is analyzed with “analyze existing results” button.

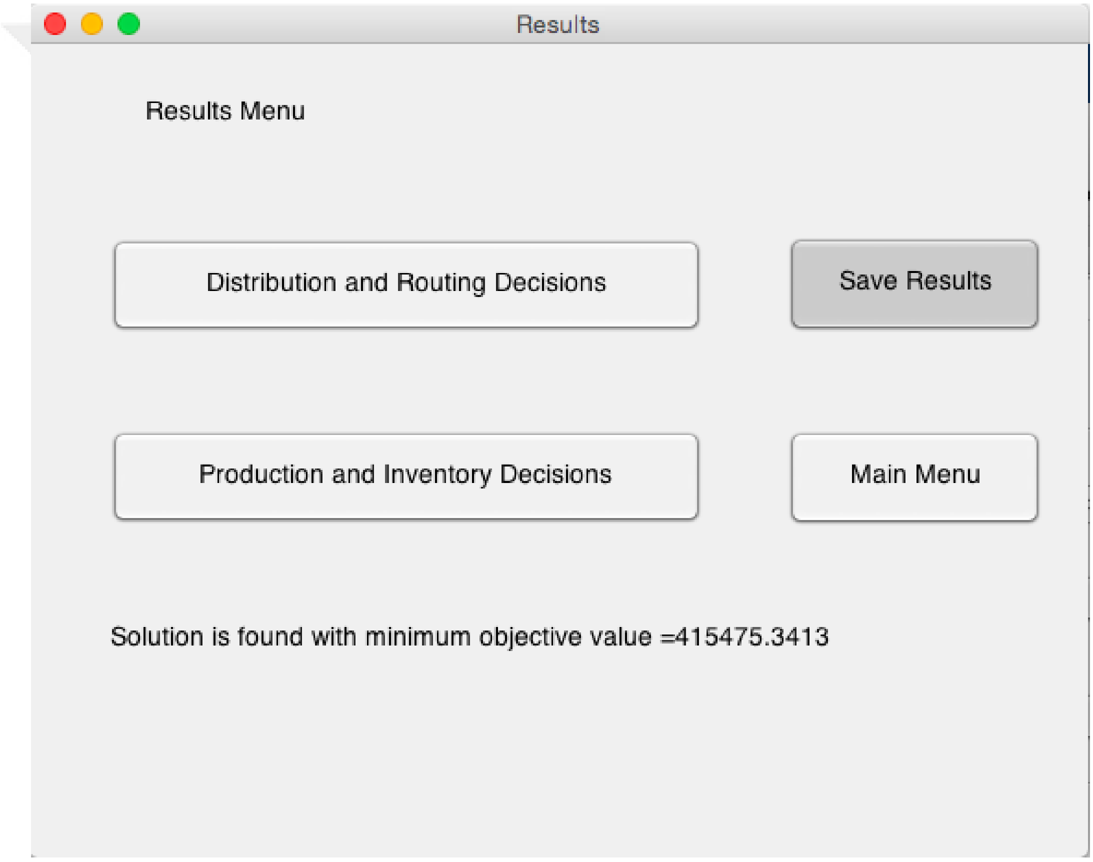
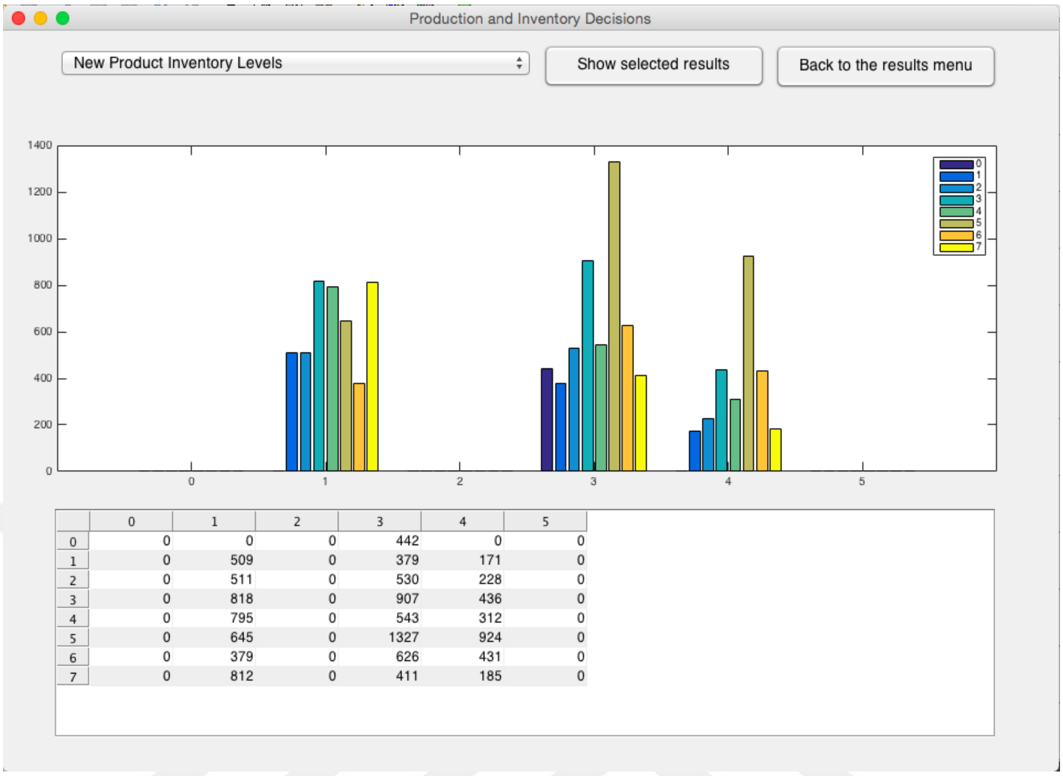


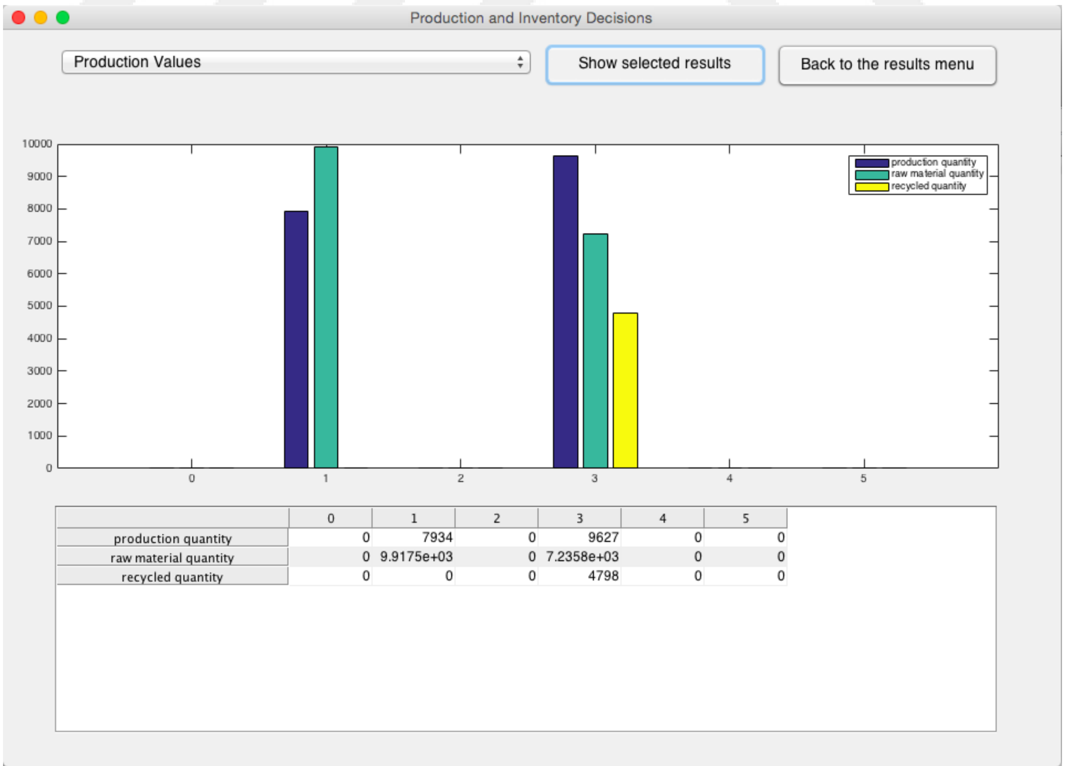
Figure 3.8. Analysis of the results screen

After solving the problem, the results are analyzed as depicted in Figure 3.8. The results are divided into two categories; distribution and routing decisions, production and inventory decisions. Furthermore, there is a saving option located in order to save results.



	0	1	2	3	4	5
0	0	0	0	442	0	0
1	0	509	0	379	171	0
2	0	511	0	530	228	0
3	0	818	0	907	436	0
4	0	795	0	543	312	0
5	0	645	0	1327	924	0
6	0	379	0	626	431	0
7	0	812	0	411	185	0

Figure 3.9. Production and inventory results screen



	0	1	2	3	4	5
production quantity	0	7934	0	9627	0	0
raw material quantity	0	9.9175e+03	0	7.2358e+03	0	0
recycled quantity	0	0	0	4798	0	0

Figure 3.10. Production and inventory results screen

New product and returned product inventory levels and production quantities are summarized in Figure 3.9 and 3.10. The graph in this GUI shows the inventory levels on each node during the planning periods. The table also shows inventory levels or production levels on each node per period.

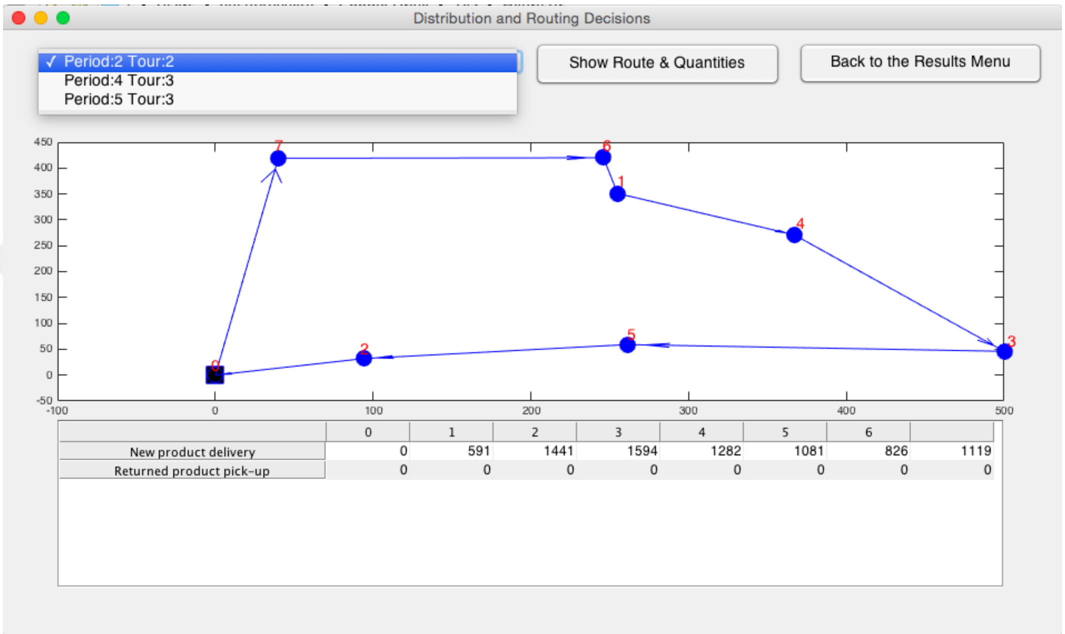


Figure 3.11. Distribution and routing decisions screen

The last form of the coded software is distribution and routing results form as given in Figure 3.11. In this form, built tours during periods and trucks are shown and when a period and tour is selected, tour and distribution amount will be displayed. Tours are represented via graph and arrows are used for make the graph to directed graph. Transportation amount of new and returned products are summarized in the table.

3.2.11. Design of Scenarios and Sensitivity Analysis

There is no real or test instances are published for the proposed problem according to our knowledge. For this reason, in addition to case study randomly generated test instances are used to the problem.

Table 3.3. Random instances generation parameters

Parameters	**Values**
New product demand (d^m)	UNIF(1000)
Returned product amounts (d^r)	UNIF(500)
Maximum inventory level (a^m)	1000+UNIF(500)
Minimum inventory level (g^m)	0
Maximum returned level(a^r)	1000+UNIF(500)
Minimum returned inventory level (g^r)	0
Holding cost of new product per period (h^m)	UNIF(10)
Holding cost of returned product per period (h^r)	UNIF(10)
Daily production capacity (B^m)	2000+UNIF(1500)*2
Fixed cost of production a day (s^m)	UNIF(50000)
Daily recycling capacity (B^r)	2000+UNIF(1000)*2
Fixed cost of recycling a day (s^r)	UNIF(50000)
Purchasing cost of new product (q^m)	UNIF(15)
Collection cost of returned product (w^r)	UNIF(15)
X and Y coordinates of production facility	(0,0)
X and Y coordinates of consumption nodes	(10+UNIF(500), 10+UNIF(500))
Distances between nodes (l)	Euclidean formula
Truck capacity (C)	(B+Brm)/v*rand()
Fixed cost of usage a truck per period (f)	UNIF(1000)
Variable cost of transportation per kilometer (c)	UNIF(10)
Maximum tour length (km) per day (L)	∑ distances between nodes (l)*rand()
Production rate (α)	rand()*2
Maximum recycling rate (β)	rand()

Table 3.3 shows the random instances parameter values. The random instance generation function which represent create_dataset(n,v,p) is coded on Matlab

software. The function is given on Appendix 3. The n denotes the number of nodes (also includes facility), v denotes the number of trucks and p denotes the planning horizon.

Demands and returned demands are created from Uniform distribution with values 1000 and 500, respectively. Maximum new and returned inventory level is calculated from 1000 + UNIF(500). This formulation is used since inventory level should be higher than a nodes daily demands or returned amounts. Minimum new and returned inventory level can be thought as safety stock level, and it is assumed to be zero. Holding costs of new and returned products are calculated from the uniform distribution (with the paramaters of 0 and 10).

Production capacity is calculated from the 2000+UNIF(1500)*2 equation. This equation ensures that the random generated production capacity should be higher enough for finding feasable solutions. For this reason, it is assumed that a production quantity should be higher than the demand for at least two points. Since, maximum demand is selected uniformly between intervals 0 and 1000, the production quantity started from the 2000. Similar calculations are valid for returned productions. Fixed costs of both production and recycling per day are assumed to be uniformly distributed between intervals 0 and 50000 unit. In new product manufacturing process, raw materials have to be added; therefore, there is a purchasing cost distributed uniformly between interval 0 and 15. A returned product should be collected; the process of this collection can cause a collection cost, which is assumed to be arisen in a uniform distribution within interval 0 to 15.

As mentioned before, the manufacturer, the recycler and the warehouse are placed in the same facility. Therefore, all of these facilities are coordinated at point (0,0). Coordinates of other consumption points which include distributors and collectors are calculated randomly between the interval 10 and 510. Each coordinate should start from 10 in order to avoid overlapping with the production facility. Distance between node pairs is computed using Euclidean distances as shown in Eq. 3.56.

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \quad (3.56.)$$

In this problem, it is assumed that trucks can have different capacities. Each truck capacities are calculated by (B+Brm)/v*rand(). B denotes the production capacity, Brm denotes the recycling capacity and v denotes the number of trucks. By using this equation, the utilization of a truck is increased so that all of the trucks can be used in an optimal solution. A truck usage cost per day (money) and its consumption per kilometer are calculated randomly of values up to 1000 and 10, respectively. Finally, maximum tour length for a truck in a day is calculated by multiplying the sum of all distances with a random number between 0 and 1.

Production rate denotes the coefficient of the production. The sum of used amounts both new and recycled materials is multiplied by production rate in order to calculate the production amount. This rate is selected as randomly between 0 and 2. Maximum recycling ratio denotes the maximum allowed recycling quantity in terms of production.

4. RESEARCH FINDINGS AND DISCUSSION

4.1. Computational Complexity of the CLSC-PIRP

The computational complexity of the mixed integer programming approach varies depending on the number of total decision variables and constraints. When the number of variables and constraints are increased, the computational complexity of the problem is increased.

In order to solve the CLSC-PIRP, the indexes of decision variables are summarized in Table 4.1. According to the results of computational complexity analysis for decision variables, a problem's computational complexity is calculated by $3n^2kt+2nkt+2nt+kt+5t$ regarding the index variables. A number of binary decision variables for the problem is calculated by $n^2kt+kt+2t$. Where n denotes to number of nodes, k denotes to number of vehicles and t denotes to number of periods.

Table 4.1. Computational complexity analysis for decision variables

Variable	*Number of nodes (n)*	*Number of trucks (k)*	*Number of periods (t)*	*Number of variables*	*Type of variable*
p			t	t	Continuous
p^m			t	t	Continuous
p^r			t	t	Continuous
I^m	n		t	nt	Continuous
I^r	n		t	nt	Continuous
Q^m	n	k	t	nkt	Continuous
Q^r	n	k	t	nkt	Continuous
X^m	n^2	k	t	n^2kt	Continuous
X^r	n^2	k	t	n^2kt	Continuous
Y^m			t	t	Binary
Y^r			t	t	Binary
Z	n^2	k	t	n^2kt	Binary
U		k	t	kt	Binary
Total binary variables				$n^2kt+kt+2t$	
Total decision variables				$3n^2kt+2nkt+2nt+kt+5t$	

Figure 4.1. shows the curve of changing total number of variables regarding number of nodes, periods and trucks. It is shown from this figure, when the number

of nodes, periods and trucks increase, the number of decision variables increase exponentially. This means this problem may not be solved optimally within reasonable time limit.

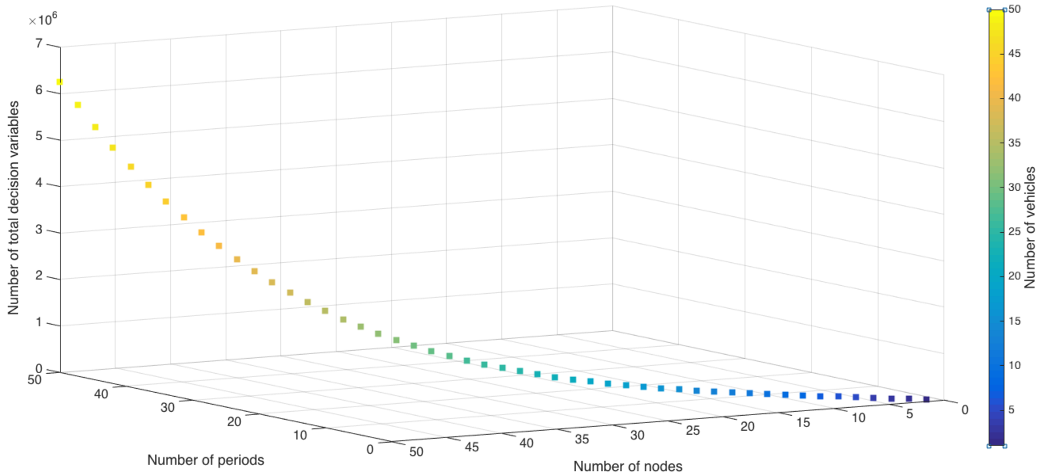


Figure 4.1. Changes on total number of decision variables regarding number of nodes, periods and trucks

The number of constraints according to indexes are also summarized in Table 4.2. According to the results of computational complexity analysis for the number of constraints that is summarized in Table 4.2, a problem's computational complexity is calculated by $n^2kt+3nkt+3kt+2nt+8t$ regarding the index variables.

According to computational complexity results, due to the fact that the total number of constraints and variables depends on number of nodes, trucks and periods, the complexity of the problem increases regarding these index values. This complexity causes the more computational time for large-scale problems.

Table 4.2. Computational complexity analysis for constraints

Constraint	*Number of nodes (n)*	*Number of trucks (k)*	*Number of periods (t)*	*Number of constraints*
Inventory balances for new products			t	t
Inventory balances for returned products			t	t
Distribution amount for the facility (new)			t	t

Table 4.2. Computational complexity analysis for constraints (Continued)

Constraint	*Number of nodes (n)*	*Number of trucks (k)*	*Number of periods (t)*	*Number of constraints*
Distribution amount for the facility (return)			t	t
Distribution amount for all nodes (new)	n	k	t	nkt
Distribution amount for all nodes (return)	n	k	t	nkt
Truck capacity constraints	n^2	k	t	n^2kt
Tour constraints	n	k	t	nkt
Tour length constraints		k	t	kt
Tour must start depot		k	t	kt
Tour must end depot		k	t	kt
Production capacity constraints			t	t
Recycling capacity constraints			t	t
Recycling rate limitations			t	t
Production rate limitations			t	t
Minimum inventory level constraints	n		t	nt
Maximum inventory level constraints	n		t	nt
Total number of constraints				$n^2kt+3nkt+3kt+2nt+8t$

Figure 4.2. shows the curve of changing total number of constraints regarding number of nodes, periods and trucks. It is shown from this figure, when the number of nodes, periods and trucks increase, number of constraints increase exponentially. This means this problem may not be solved optimally within reasonable time limit.

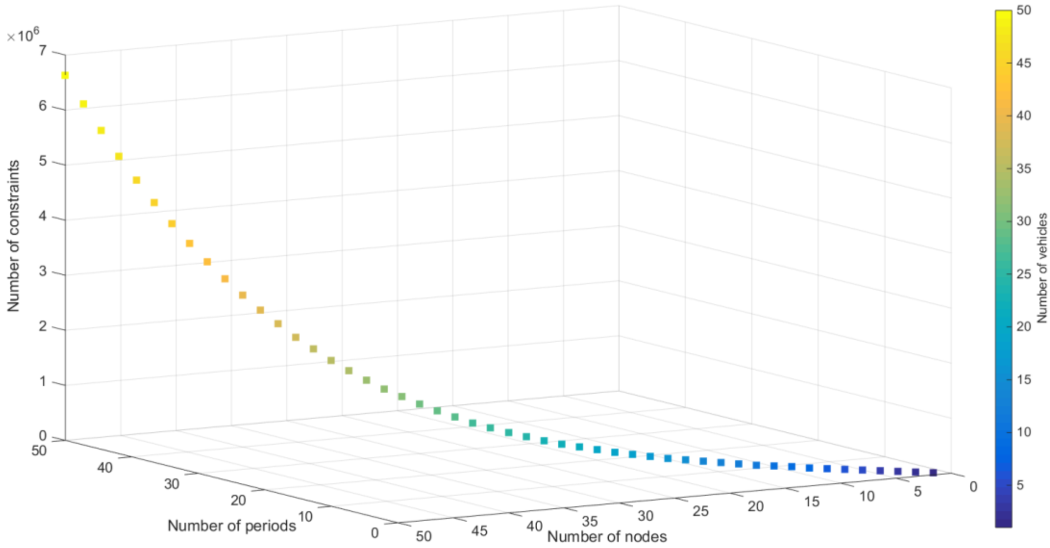


Figure 4.2. Changes on number of constraints regarding number of nodes, periods and trucks

4.2. Sensitivity Analysis of the CLSC-PIRP

As can be realized in linear programming models, the model's input parameters are supplied by the constraints and the coefficients of the objective model. Accordingly, the value of these coefficients yields the optimal solution which is obtained by the simplex method. However, in practice, these values rarely meet absolute certainty, since a majority of them are considered functions including uncontrollable parameters. Any adjustments appearing in the values of these coefficients would cause the linear programming problem to be changed and as a result cause a mislead to the optimal solution concluded earlier. In order to find a way to achieve an overall strategy which meets the criteria of the various contingencies it should be investigated that how optimal solution varies according to the changes of coefficient values. This approach is referred to the sensitivity analysis (Ravindran et al., 2007).

In order to show the effects of estimated parameter's values that are used in the problem, the sensitivity analysis has been applied. Five nodes and seven days planning problem that generated randomly is used for evaluating the sensitivity. The CLSC-PIRP model is complicated even if the number of nodes, periods and trucks are selected in small integer values. For this reason, it is hard to apply classical sensitivity analysis to this problem. Therefore, holding, preparation, fixed and variable transportation, purchasing and collection cost parameters are focused in order to measure sensitivity of the CLSC-PIRP. All these parameter values are changed in the range ± 50 percentage of their selected values and the sensitivity of the model is depicted in Figure 4.3 and Figure 4.4. The graphs show whether the solution is changed or not.

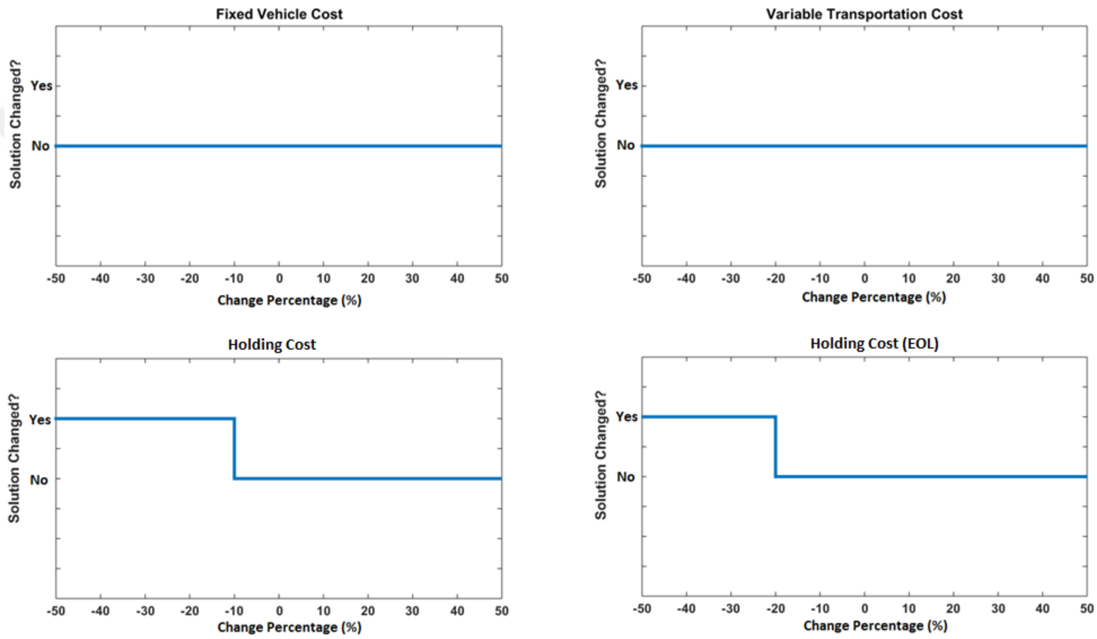


Figure 4.3. Results of the solution changes regarding transportation and holding costs

According to results are given in Figure 4.3, cost parameters that are related with transportation activities do not affect the solution set. In other words, this model is not sensitive to transportation costs. When the holding costs are decreased more than 10 percent, the solution is changed. If the holding cost predicted more than 10 percent of real value, the optimal solution set is changed. Similar results are obtained for returned product holding costs. The only difference is that the returned product holding costs are less sensitive than new product holding costs. The solution is changed when the returned product holding costs occurred less than 20 percent. It can be observed from this values, holding inventory instead of production or recyling is not too much benefica

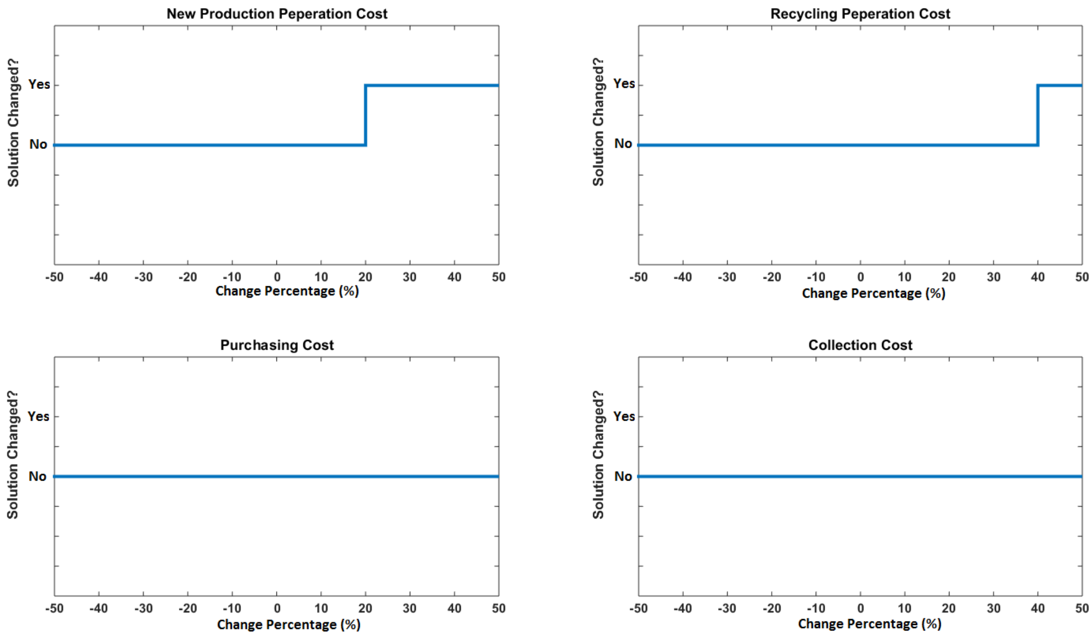


Figure 4.4. Results of the solution changes regarding preperation and purchasing costs

According to results that are given in Figure 4.4, cost parameters that are related with purchasing activities do not affect the solution. In other words, this model is not sensitive to purchasing and collection costs. When the production preparing costs are increased more than 20 percent, the solution is changed. If the production preparing cost predicted more than 20 percent of real value, the optimal solution is changed. A similar condition is valid for recycling preparation costs. The only difference is that returned product holding costs are less sensitive than new product holding costs. The solution is changed when the returned product holding costs occurred less than 40 percent.

Figure 4.5 and 4.6 show the sensitivity analysis results on objective function. When the slope of an objective function curve is changed, it can be understood that the solution is changed. Because, when the parameters are changed, objective values are changed; however, if a solution set is changed, the objective function slope is changed regarding the new solution set.

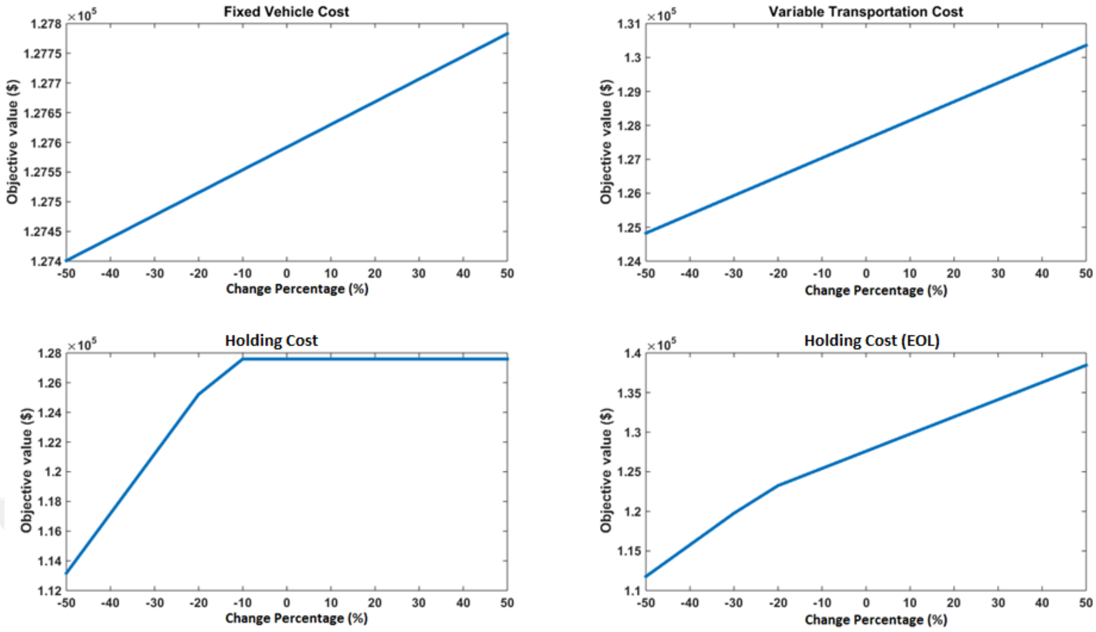


Figure 4.5. Results of the objective value changes regarding transportation and holding costs

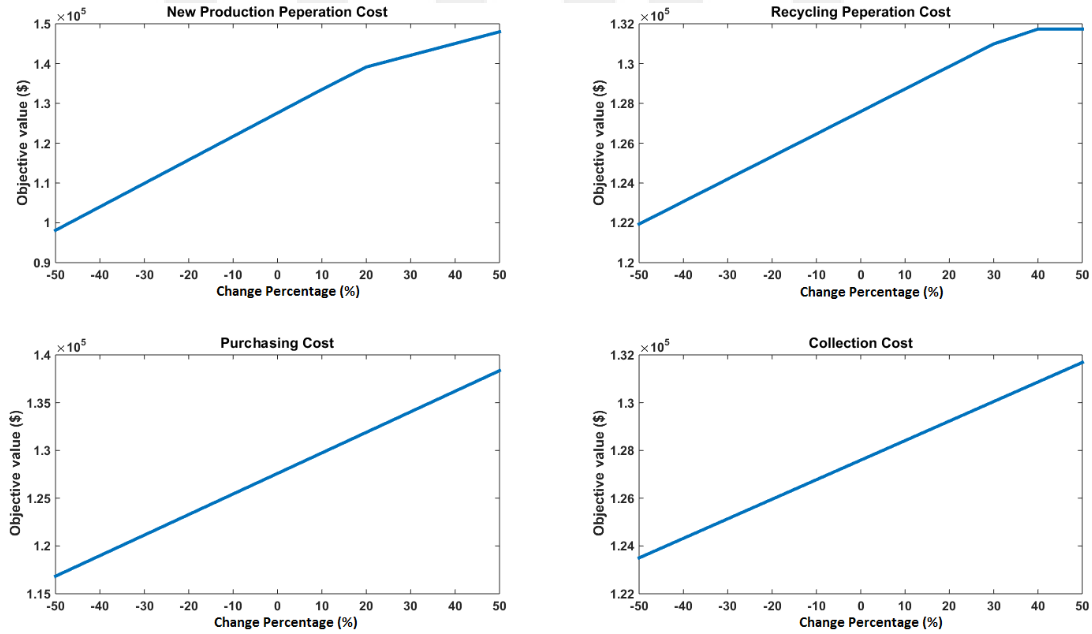


Figure 4.6. Results of the objective value changes regarding preperation and purchasing costs

It is observed that when the holding cost is decreased, the model try to decrease the number of production/recycling periods. In other words, keeping inventory will become so reasonable than production/recycling.

Furthermore, an experimental design is built in order to evaluate the effects of cost parameters when the increase percentage is more than one hundred. In this experimental design, three ratio are selected as factors;

- truck usage fixed cost divided by variable cost (level values are selected one, five and ten)
- new product manufacturing preparation cost divided by unit holding cost of new product (level values are selected ten, a hundred and a thousand)
- returned product recycling preparation cost divided by unit holding cost of returned product (level values are selected ten, a hundred and a thousand)

The test problem of the experimental study is created randomly as mentioned in section 3.1.2. The number of periods and nodes are selected as seven days and five points, respectively. Detailed analysis results which includes number of production days, number of recycling days, number of routes, sum of new and returned inventory levels are given in Appendix 4. Table 4.3 summarizes these results.

According to the results, the solution changes significantly. For example, number of production days increases from one to five like recycling days. Number of routes are more resistant than others, because it changes in the range of three and five. Sum of new and returned inventory varies between about five thousands to sixteen thousands. Therefore, it can be concluded, the model is sensitive when the deviation occurs more than one hundred percent.

Table 4.3. Results of experimental design

Name	*Minimum*	*Maximum*	*Mean*	*Std. Dev.*
Objective ($)	251117.052	584473.998	379386.1784	118229.3165
Number of Production Day	1	5	3.407407407	0.930643254
Number of Recycling Day	1	5	2.333333333	1.358732441
Number of Delivery	3	5	3.555555556	0.69798244
Sum of Inventory	6037	15581	8916.888889	2732.774898
Sum of EOL Inventory	5164	15649	10497.11111	3892.821187

Figure 4.7 shows the main effects of the factors on the objective. According to the plot, when the truck usage fixed cost increases from one to five, objective value gives a too negative respond. However, when the ratio is equal to more than five, the objective value is decreasing less slightly. It can be concluded from this ratio, when the fixed/variable cost increases, objective value is increased. But when it increases too much then objective value decreases.

According to results of production preparation /holding cost ratio, objective increases when the ratio is increased. Therefore, holding cost is not effected too much with respect to production preparation cost. Finally, the results of returned product's recycling preparation /holding cost ratio show that increases of this ratio effects the decisions, similarly to truck fixed/variable cost ratios. Mean objective value is increased first, however it starts decreasing after the ratio increased from a specified point. This means, when this ratio increased too much, decision of the model changes like as transportation costs.

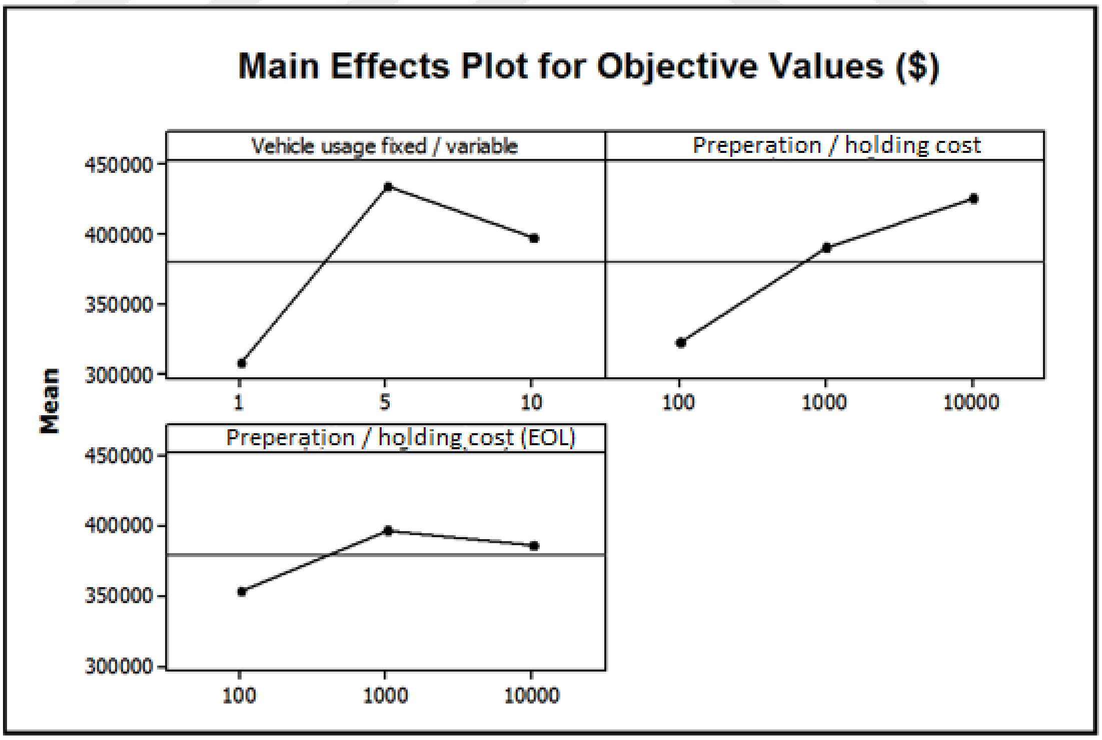


Figure 4.7. Main effects plot for objective values of the design

Figure 4.8 shows the interactions between factors on the objective value. According to the plot, when the truck usage fixed/variable cost and preparation/holding cost increase to ten, the objective value becomes too high. It is noticable, because if both of the ratios are increased dramatically, there is no option such as produced more, transport more. This result is similar for truck usage fixed/variable cost ratio and returned preparation/holding cost ratio. However, this is more slightly increasing regarding objective. Interaction plots says that the most sensitive case on objective values is increasing both of the preparation/holding ratios to one thousand. As the number of nodes and periods increase, we observe an increase in CPU time. However, when the number of node is low, the increment in the number of periods does not affect CPU time, since the number of binary variables and constraints increase at the high level of the number of nodes.

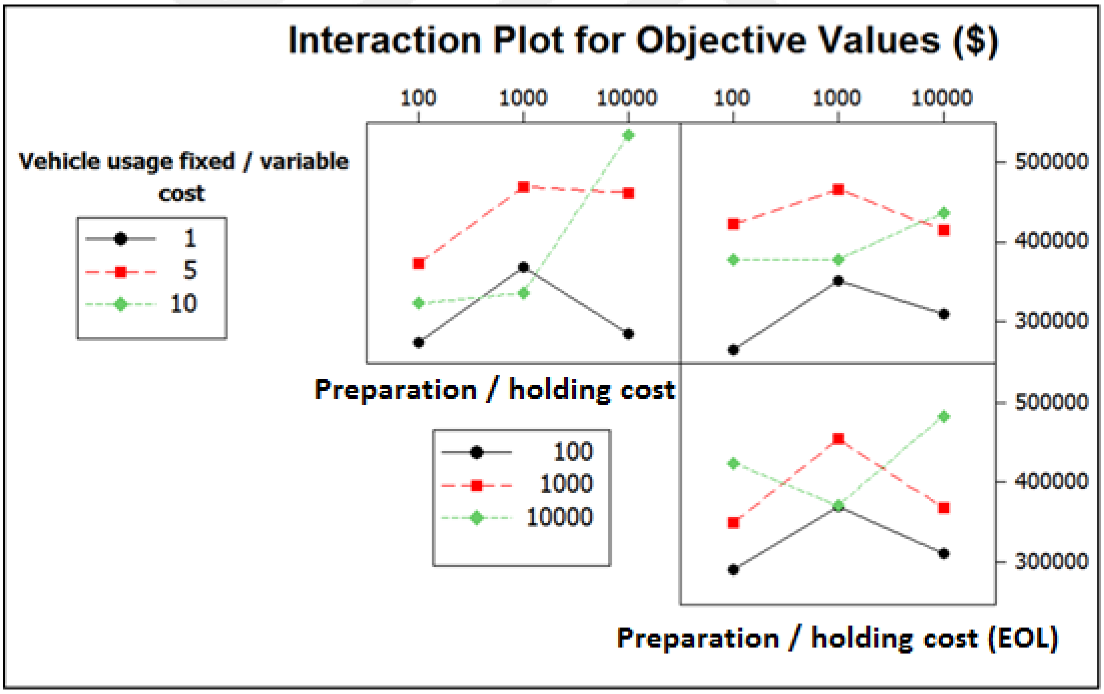


Figure 4.8. Interaction plot for objective values of the design

4.3. Case Study Results

As mentioned before, a real margarine supply chain is selected as a case study of this study. In this case, the planning horizon is selected within fifteen-days duration. In the selected planned horizon, there are six different points at which new product demand or returned products are acquired. Figure 4.9 shows the map of the cities in which have a demand of new or returned products.

Distance matrix between cities is illustrated in Table 4.4. The manufacturer, the warehouse and the recycler are located at City 1. Other cities are denoted as consumption nodes. Maximum distances between cities are calculated with a range of 1361 km among City 3 and City 5. Correspondingly, minimum distances between cities are calculated as 192 km between City 1 and City 2.

Table 4.4. Distances among cities

Distances	***City 1***	***City 2***	***City 3***	***City 4***	***City 5***	***City 6***
City 1	0	192	939	394	525	356
City 2	192	0	1044	222	369	548
City 3	939	1044	0	1112	1361	551
City 4	394	222	1112	0	249	645
City 5	525	369	1361	249	0	881
City 6	356	548	551	645	881	0

Demand and returned quantities in the 15- day period are clarified in Table 4.5. According to the table, while the maximum new product demand is stated as an amount of 1.16 ton per day, returned product demand is stated as an amount of 9.36 tones for the planning horizon. Due to the fact that returned products were damaged or exceeded the shelf life, this amount is accumulated during that shelf life consequently this amount is higher than new ones which are daily demanded.

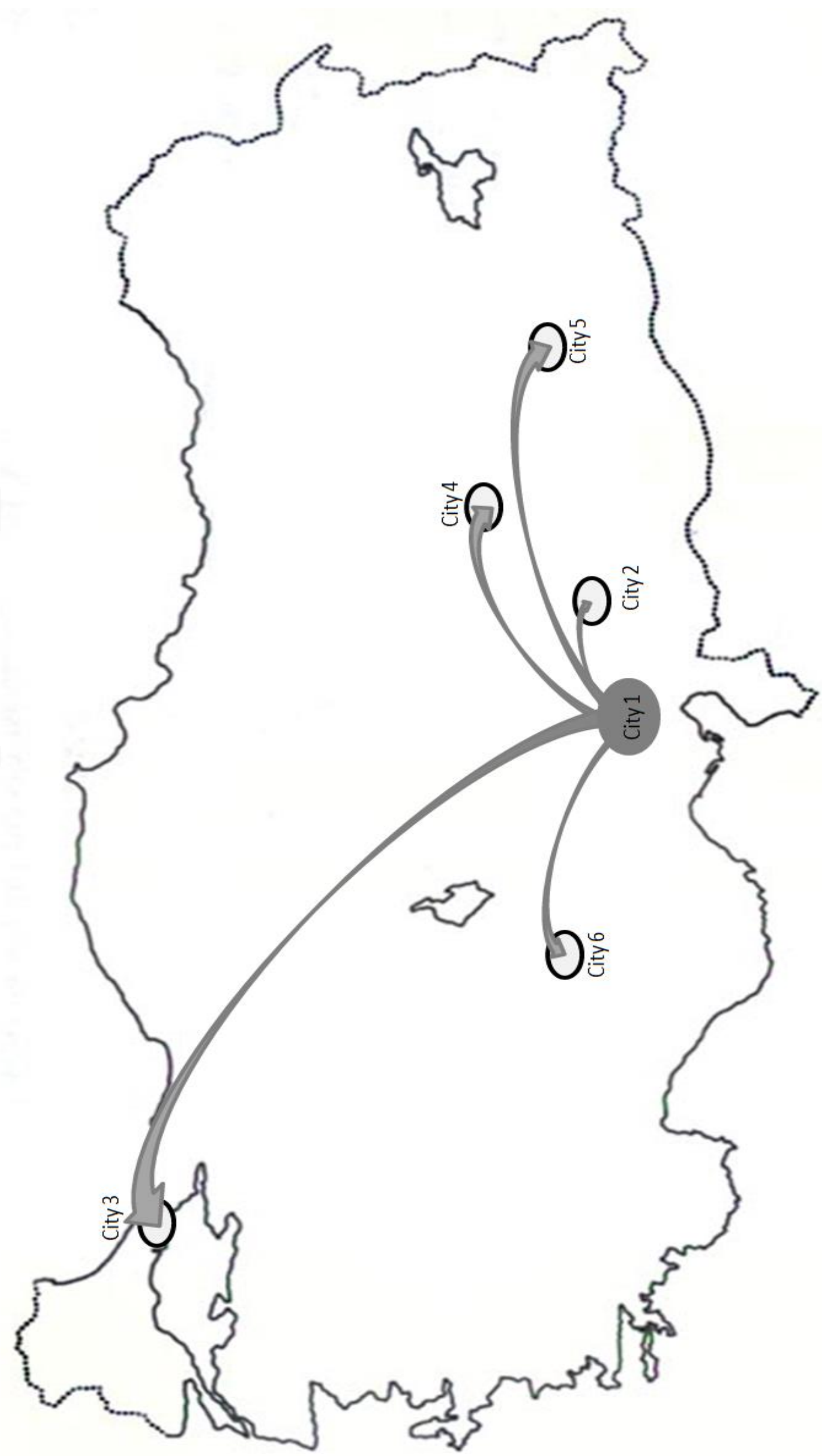


Figure 4.9. The closed loop supply chain map for the planning horizon

Table 4.5. Demands and returned quantities

	City	*Period (day)*											
		3	4	5	6	8	9	10	11	12	13	14	15
New product demand (ton)	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0.35	0	0	0	0	0	0
	2	0.043	1.355	0	0.794	0	0.973	0	1	0	1.166	0.66	0
	3	0	0.23	0	0	0	0	0	0	0.5	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	1	1
	5	0	1	0	0	1	0	0	0	0	0	0	0
Returned amount (ton)	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	9.36	0	0	0	0	0	0	0	9.36	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	3.68	0	0	0	0	0
	5	0	0	7	0	5.76	0	0	0	0	0	0	0

Other parameters used in modeling are summarized in Table 4.6. Transportation operations were carried out with the trucks that have 3 different capacities (4.5, 14 and 23 ton). Daily production and recycling capacity are 1.68 ton and 0.8 ton, respectively. The preparation costs / holding costs ratio for manufacturing and recycling are equal to 432 and 368.57, respectively. Finally, the truck usage fixed costs / variable costs ratio is equal to 180, 560 and 920 regarding the truck capacity levels. In the margarine production process, water is added to the emulsion premix tank. Therefore, the production amount occurs more than included raw crude oil amount. Actual production amount is calculated by multiplying the raw material amount to production rate which is equal to 1.19 in this case. The recycling amount must be lower than a spesific percentage of production amount. For this reason, a maximum allowable recycling amount is a rate of production amount which is equal to 0.1 in this case.

Table 4.6. Case study parameters

Parameters	
Production & inventory related parameters	**Values**
Daily production capacity (ton)	1.68
Daily recycling capacity (ton)	0.80
Preparation cost/holding cost	432.00
Preparation cost/holding cost (returned products)	368.57
Maximum recycling rate	0.1
Production rate	1.19
Transportation related parameters	**Values**
Truck use fixed/variable costs (for each truck type) (TL)	180-560-920

The CLSC-PIRP and two stage approach mathematical models are modeled and solved by GAMS optimization software with a personal computer has 3.6 GHz Intel CPU and 16 GB ram. The case problem is solved in reasonable time limit as long as it is not needed to solve by proposed decomposition heuristic method.

4.3.1. The Closed Loop Supply Chain Coordinated Production-Inventory-Distribution-Routing Problem Results

In this section, the case problem is modeled as the CLSC-PIRP and is solved. An amount of $ 57,106.16 was found optimal as the total cost of this case after 32.29 seconds of CPU time.

According to Table 4.7, production, recycling and purchased raw material quantities each period are demonstrated. Only the production days are given in this table in order to ease of illustration. Generally, it seems the production capacity utilization rate has appeared to one, except second period. When the recycling was operated, maximum allowable quantity has been recycled. Need of raw material to be purchased has been calculated respecting production and recycling quantities.

Table 4.7. Production decisions of CLSC-PIRP for case problem

Quantities (ton)	***Periods (day)***						
	2	**3**	**4**	**8**	**9**	**13**	**14**
Production	0.991	1.68	1.68	1.68	1.68	1.68	1.68
Recycling	-	0.168	0.168	0.168	0.168	-	-
Raw material	0.883	1.244	1.244	1.244	1.244	1.412	1.412

Table 4.8 shows the inventory levels of both new and returned products on each node and period. Only the places and days which hold inventory are shown in this table for ease of illustration. According to results for new product inventory levels, production facility and distributors that are placed in City 3, City 5 and City 6 have been permitted to hold the inventory. Maximum new product inventory level has been actualized 2.628 ton that placed in production facility at third day.

Table 4.8. New inventory levels for the case problem

Periods (day)	**New Inventory Levels (ton)**			
	City 1 (Production Facility)	**City 3**	**City 5**	**City 6**
2	0.991	-	-	-
3	2.628	-	-	-
4	0.123	1.2	-	0.4
5	0.123	1.2	-	0.4
6	0.123	0.406	-	0.4
7	0.123	0.406	-	0.4
8	1.203	0.406	-	-
9	0.766	1.2	-	-
10	0.766	1.2	-	-
11	0.766	0.2	-	-
12	0.266	0.2	-	-
13	0.32	0.66	-	-
14	0.6	-	0.4	-

As its demonstrated on Table 4.9, maximum returned inventory level has been actualized 14.5 ton that placed in recycling facility at thirteenth, fourteenth and fifteenth days. Returned inventory levels seem higher than new inventory levels due to the collection demand of returned product and limitations on recycling quantities.

Table 4.9. Returned inventory levels for the case problem

Periods (day)	**Returned Inventory Levels (ton)**			
	City 1 (Production Facility)	**City 3**	**City 5**	**City 6**
2	-	-	-	-
3	4.332	4.86	-	-
4	8.434	0.59	-	-
5	8.434	0.59	-	7
6	8.434	0.59	-	7
7	8.434	0.59	-	7
8	14.026	0.59	-	7
9	14.448	-	-	7
10	14.448	-	3.68	7
11	14.448	-	3.68	7
12	14.448	9.36	3.68	7
13	14.5	9.308	3.68	7
14	14.5	9.308	3.68	7
15	14.5	9.308	3.68	7

Table 4.10. Distribution amounts of tours

Tours	*Pickup/Delivery Amount*	*City 2*	*City 3*	*City 4*	*City 5*	*City 6*
Period 3	New product	0	0.043	0	0	0
	Return product	0	4.500	0	0	0
Period 4	New product	0	2.555	0.23	0	1.4
	Return product	0	4.27	0	0	0
Period 8	New product	0	0	0	0	0.6
	Return product	0	0	0	0	5.76
Period 9	New product	0.35	1.767	0	0	0
	Return product	0	0.59	0	0	0
Period 12	New product	0	0	0.5	0	0
	Return product	0	0	0	0	0
Period 13	New product	0	1.626	0	0	0
	Return product	0	0.052	0	0	0
Period 14	New product	0	0	0	1.4	0
	Return product	0	0	0	0	0
Period 15	New product	0	0	0	0.6	0
	Return product	0	0	0	0	0

Distribution quantities picked-up and delivered on each tour during the planning horizon are shown in Table 4.10. Eight tours have been required to derive demands of pick-up and delivery. Maximum new product delivery and returned product delivery amount has been found as 2.555 ton and 5.76 ton, respectively.

The distribution routes that are depicted in Figure 4.10-15 have been created by six different trips during the periods. The first trip has been travelled at the third period. The second trip has been travelled at the fourth and the thirteenth periods. The third trip has been travelled at the ninth period. The fourth trip has been travelled at the twelfth period. The fifth trip has been travelled at the fourteenth and the fifteenth periods. The sixth trip six has been travelled at the eighth period. Therefore, eight trips have been travelled by different capacitated trucks during the planning horizon.

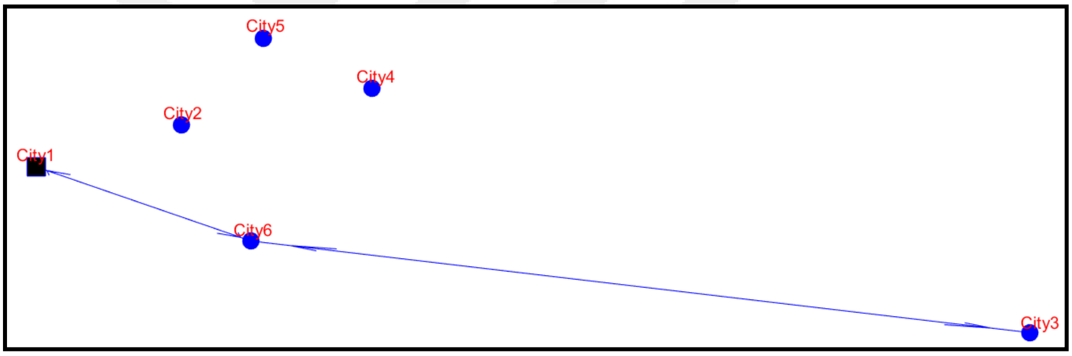


Figure 4.10. Truck route for the first trip

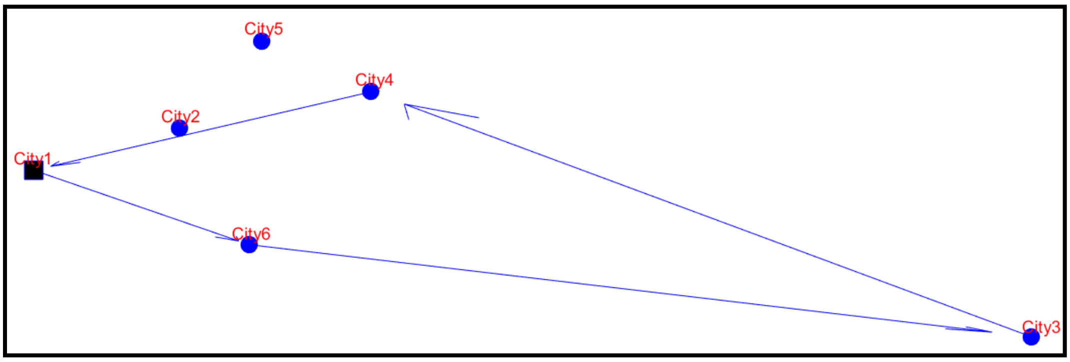


Figure 4.11. Truck route for the second trip

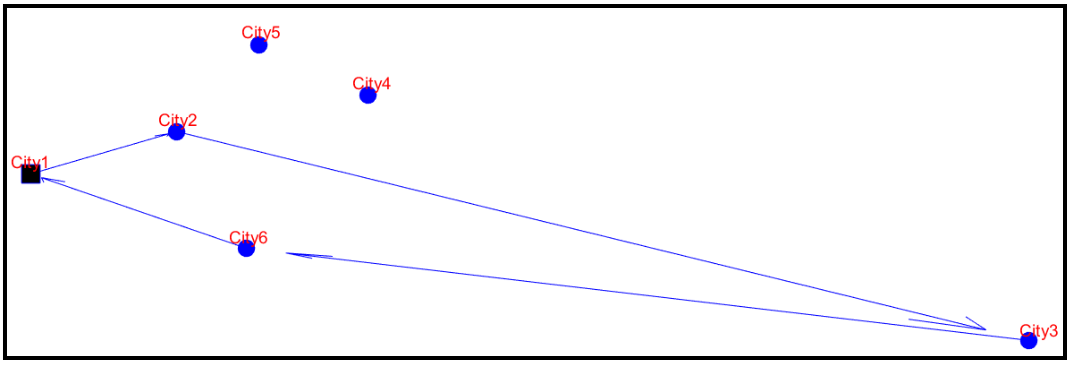


Figure 4.12. Truck route for the third trip

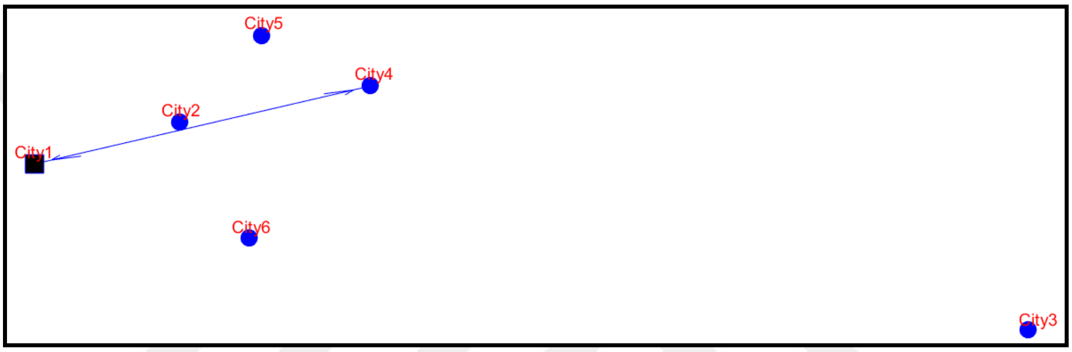


Figure 4.13. Truck route for the fourth trip

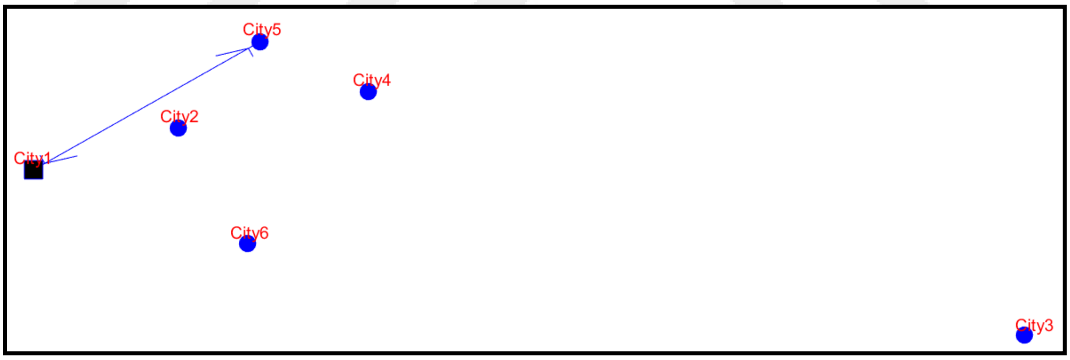


Figure 4.14. Truck route for the fifth trip

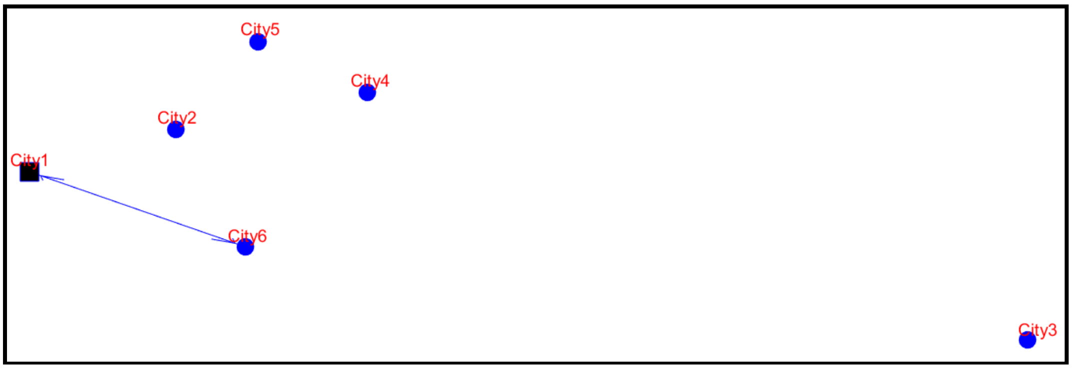


Figure 4.15. Truck route for the sixth trip

4.3.2. The Two-stage Approach Results

In this section, the case problem is modeled as the two-stage approach model and is solved. An amount of $ 64,996.16 was found optimal as the sum of total cost of the FSP and BSP for this case after 72.04 seconds of CPU time.

According to Table 4.11, production, recycling and purchased raw material quantities each period are demonstrated. Only the production days are given in this table for ease of illustration. Generally, it seems that the production capacity utilization rate became one, excluding the second period. When the recycling was operated, maximum allowable quantity was recycled. The need of raw material to be purchased has been calculated in respect to production and recycling quantities.

Table 4.11. Production decisions of CLSC-PIRP for case problem

Quantities (ton)	***Periods (day)***						
	2	**3**	**4**	**8**	**9**	**13**	**14**
Production	0.991	1.68	1.68	1.68	1.68	1.68	1.68
Recycling	-	0.168	0.168	0.168	0.168	-	-
Raw material	0.883	1.244	1.244	1.244	1.244	1.412	1.412

Table 4.12. New inventory levels for the case problem

Periods (day)	**New Inventory Levels (ton)**			
	City 1 (Production Facility)	**City 3**	**City 4**	**City 6**
2	-	0.991	-	-
3	1.68	0.948	-	-
4	0.383	0.794	0.146	0.4
5	0.383	0.794	0.146	0.4
6	0.383	-	0.146	0.4
7	0.383	-	0.146	0.4
8	1.463	-	0.146	-
9	0.62	1.2	0.146	-
10	0.62	1.2	0.146	-
11	0.62	0.2	0.146	-
12	0.266	0.2	-	-
13	0.32	0.66	-	-
14	1	-	-	-

Table 4.12 shows the inventory levels of both new and returned products on each node and period. Only the places and days which hold inventory are shown in this table in order to ease of illustration. According to results for new product inventory levels, production facility and distributors that are placed in City 3, City 4 and City 6 have been permitted to hold the inventory. Maximum new product inventory level has been actualized as1.68 ton that has been placed in production facility at the third day.

As demonstrated in Table 4.13, maximum returned inventory level has been actualized as 14.5 ton that has been placed in recycling facility at the fifth, sixth and seventh days.

Table 4.13. Returned inventory levels for the case problem

Periods (day)	Returned Inventory Levels (ton)			
	City 1 (Production Facility)	City 3	City 5	City 6
3	8.908	0.284	-	-
4	8.74	0.284	-	-
5	14.5	0.284	-	1.24
6	14.5	0.284	-	1.24
7	14.5	0.284	-	1.24
8	14.332	0.284	-	7
9	14.448	-	-	7
10	14.448	-	3.68	7
11	14.448	-	3.68	7
12	14.448	9.36	3.68	7
13	14.448	9.36	3.68	7
14	14.448	9.36	3.68	7
15	14.448	9.36	3.68	7

Distribution quantities have been picked-up and delivered on each tour during the planning horizon are shown in Table 4.14. Eleven tours have been required to derive demands of pick-up and delivery. Maximum new product delivery and returned product delivery amount have been found to be 2.173 ton and 9.076 ton, respectively.

Table 4.14. Distribution amounts of tours

Tours	*Pickup/Delivery Amount*	*City 2*	*City 3*	*City 4*	*City 5*	*City 6*
Period 2	New product	0	0.991	0	0	0
	Return product	0	0	0	0	0
Period 3	New product	0	0	0	0	0
	Return product	0	9.076	0	0	0
Period 4	New product	0	1.201	0.376	0	1.4
	Return product	0	0	0	0	0
Period 5	New product	0	0	0	0	0
	Return product	0	0	0	0	5.76
Period 8	New product	0	0	0	0	0.6
	Return product	0	0	0	0	0
Period 9-1	New product	0.35	2.173	0	0	0
	Return product	0	0	0	0	0
Period 9-2	New product	0	0	0	0	0
	Return product	0	0.284	0	0	0
Period 12	New product	0	0	0.354	0	0
	Return product	0	0	0	0	0
Period 13	New product	0	1.626	0	0	0
	Return product	0	0	0	0	0
Period 14	New product	0	0	0	1.0	0
	Return product	0	0	0	0	0
Period 15	New product	0	0	0	1.0	0
	Return product	0	0	0	0	0

The distribution routes have been created by six different trips during the periods. The trips are the same with the CLSC-PIRP results that are given in Figure 4.10-15.

During the planning horizon, there are eight trips have been travelled by different capacitated trucks for delivering the new products. The first trip that is shown in Figure 4.10, has been travelled at the second and thethirteenth periods. The second trip that is shown in Figure 4.11, has been travelled at the fourth period. The third trip that is shown in Figure 4.12, has been travelled at the ninth period. The fourth trip that is shown in Figure 4.13 has been travelled at the twelfth period. The fifth trip that is given in Figure 4.14, has been travelled at the fourteenth and the fifteenth periods.

Finally, the sixth trip that is shown in Figure 4.15, has been travelled at the eighth period.

During the planning horizon, there are three trips have been travelled by different capacitated trucks for picking up the returned products. The first trip that is shown in Figure 4.10, has been travelled at the third and the ninth periods. The sixth trip that is shown in Figure 4.15, has been travelled at the fifth period.

4.3.3. Comparison of the Methods

The case study problem is modeled and solved as both CLSC-PIRP and two-stage approaches. The results are summarized in Table 4.15. According to results, the coordinated forward and backward decisions were insighted better logistic planning. Therefore, the total number of tours that must be done during the planning period was occurred less on the CLSC-PIRP approach. For this reason, total chain operational cost decrased on the CLSC-PIRP. Furthermore, in the CLSC-PIRP approach, CPU time actualized half of the two-stage approach.

Table 4.15. Comparison of the methods for case study

Indicator	***CLSC-PIRP***	***Two-stage approach***
Objective function value ($)	57,106.16	64,996.16
CPU time (sec)	32.29	72.04
Number of tours	8	11
Number of production days	7	7
Number of recycling days	4	4
Sum of inventories	17.876	17.876
Sum of return inventories	297.56	297.56

4.4. Proposed Decomposition Heuristic Parameter Setting

An heuristic method is needed for setting up some user-defined parameters. Therefore, the user-defined parameters should be set before evaluating the decomposition heuristic method. For this reason, this section presents the parameter setting results.

In the decomposition heuristic approach, the simulated annealing algorithm is used for determining the best routes during the periods. In simulated annealing algorithm, there are some user-defined operations as mentioned in section 3.2.9.2.

User-defined parameters influence the algorithm performance so that the algorithm can reach the best solution by making few iterations within the best parameter values. According to our limited knowledge, there is no method proposed in order to find the best user-defined parameter values. For this reason, in this study, several different user-defined values were analyzed on a test instance thereby the best parameters values were achieved. The test instance was generated randomly for fifteen nodes and seven periods.

The initial solution is generated randomly. The cost function is calculated from the evaluation model's objective function value. Number of iteration is set to one thousand.

Initial temperature (T) has ranged from one thousand to twenty five thousands by increased a thousand. Figure 4.16 illustrates deviation from optimal and solution times of different temperature values. The first part of the figure shows heuristic approach has solved the problem more quicker than mathematical programming approach. The second part shows the heuristic approach has easily reached the optimal value within few deviation. It can be understood from the figure, when the temperature value is set to the 3000, gap between the heuristic and the optimal solution is calculated about ten percent. All other temperature values has deviated from the optimal solution less than ten percent. Therefore, temperature value did not affect the results too much. The best objective value was obtained when the temperature value equals to 19000. The least solution time was also acquired when the temperature was set to 19000. For this reason, the initial temperature value is set to 19000.

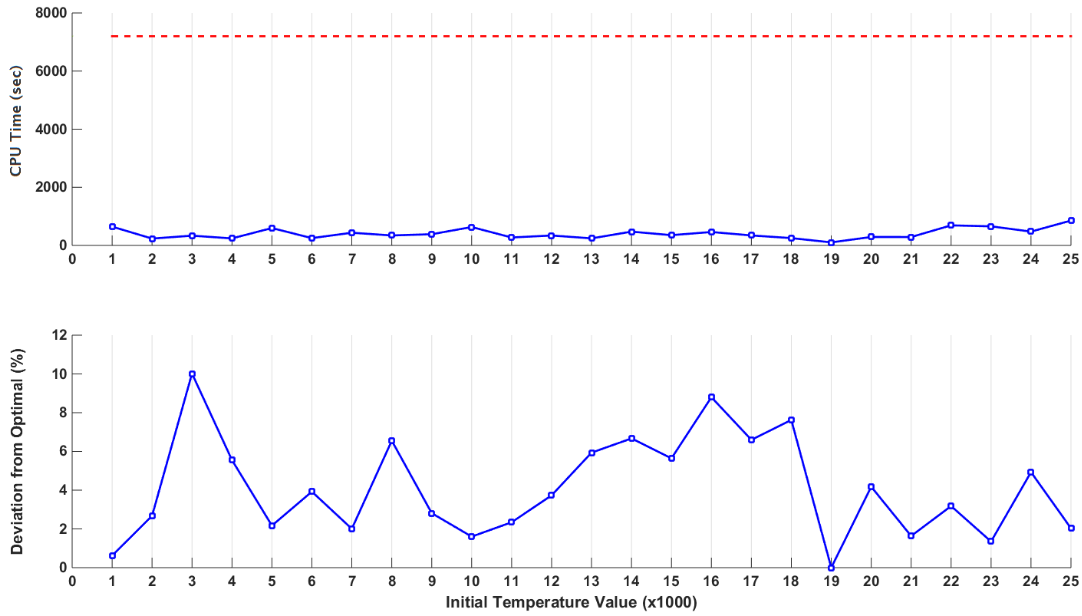


Figure 4.16. Comparison of catching optimal solution and CPU time among temperature

Temperature reduction type is assumed as linear type. This means temperature is updated linearly by multiplying the reduction ratio (α) in each iteration. In order to show the effect of the ratio, it is ranged from 0.1 to 0.99 increased by 0.1. Figure 4.17 illustrates gap between the heuristic and the optimal and solution times of different temperature reduction values. The first part of the figure shows that the temperature reduction ratio does not influence the solution time too much. The second part shows the heuristic approach can easily find the optimal value within few gap. It can be understood from the figure, only the first instance is (alfa set to 0.1) deviated from the optimal solution at most about eleven percent. Therefore, reduction ratio did not affect the results too much. The best results were obtained when the temperature value equals to 0.9. Therefore, the temperature reduction ratio is set to 0.9.

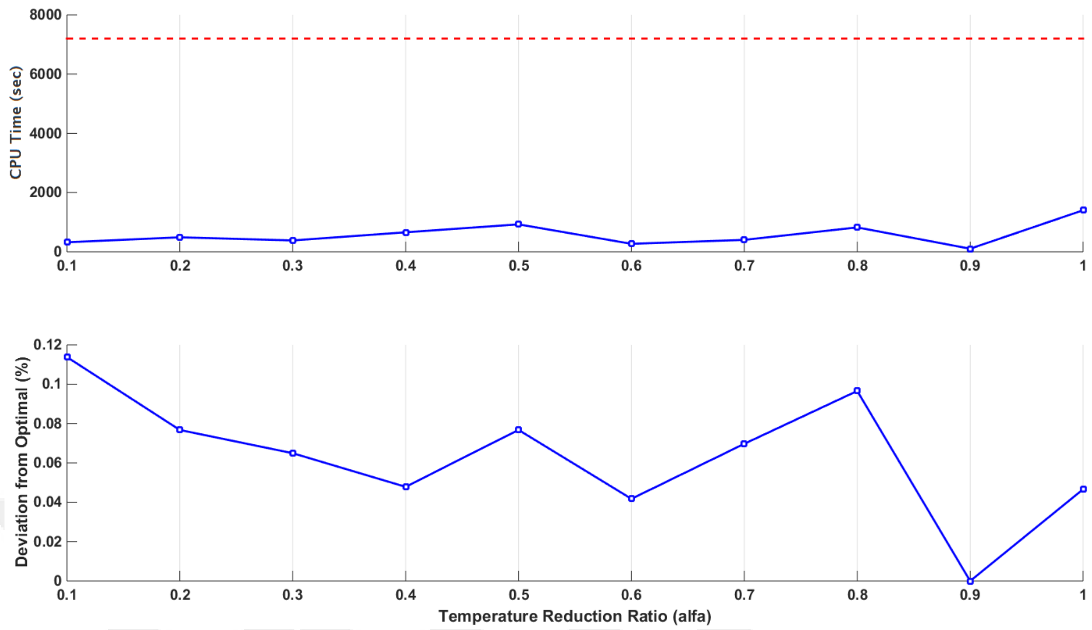


Figure 4.17. Comparison of catching optimal solution and CPU time among temperature reduction ratio

Finally, in order to show the effect of the number of neighbor solutions that is searched in each period, it is ranged from one to ten increased by one. Figure 4.18 illustrates deviation from optimal and solution times of different number of neighbor solution (Cs) values. The first part of the figure shows heuristic approach solved the problem slower when the number of neighbor solution searched was increased. The second part shows the heuristic approach could easily reach the optimal value within at most about fifteen percent deviation. It can be understood from the figure, when the number of neighbour solutions was selected less than 5, the gap between the heuristic and optimal solutions appeared more precisely than others. The Cs value affects the results more than other parameters (temperature and reduction). The best results are obtained when the Cs value equals to 5. Solution time is also better when the Cs equals to five, so the Cs is set to five.

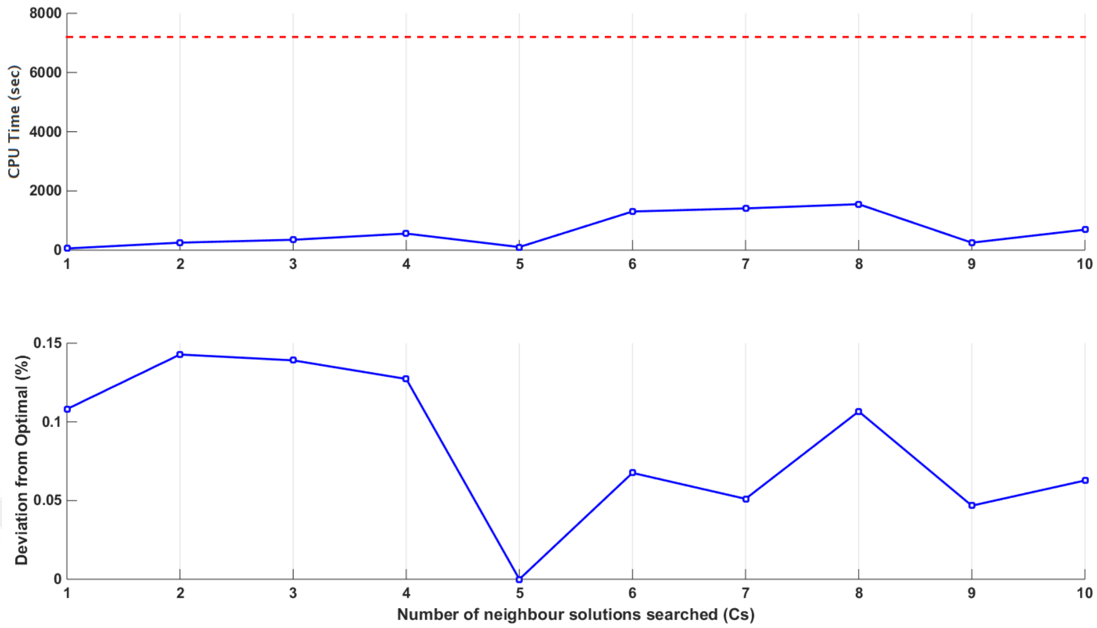


Figure 4.18. Comparison of catching optimal solution and CPU time among number of neighbor solutions

4.5. Scenario Analysis

In this section, scenario analysis is conducted in order to evaluate behaviors of both models on different conditions. There are several parameter and indexes that are influenced both mathematical models' solutions. For this reason, in the scenario analysis effects of indexes have been investigated. A factorial design has been derived and the results were presented.

Number of nodes and periods are selected as drivers (or factors) of the design. Number of nodes has four levels; five, ten, fifteen and twenty. Similarly, number of periods has two levels; five and ten. Therefore, these leads to create 4x2 type general factorial design. Each experiment is replicated two times. The response variables are selected as objective values of the optimal solutions and CPU times.

The test instances are generated randomly as mentioned in previous chapter. CPLEX options are set as follows; (i) time limit is set to 43200 seconds (12 hours) for each model. (ii) the relative gap between integer and best found solution is set to 0.0001.

4.5.1. The Closed Loop Supply Chain Coordinated Production-Inventory-Distribution-Routing Problem Results

Table 4.16 summarizes the results obtained from solving the CLSC-PIRP. The instances that used on scenario analysis are generated randomly, therefore objective value differs too much. Another reason for deviation of the objective value is when the number of nodes and periods were increased, the chain costs could be increased. CPU time column shows that when the problem gets complicated, the CPU time increased rapidly. This is caused by the complexity of the CLSC-PIRP. The average objective value was calculated 836 353 money unit within the average solution time was occurred 4.5 hours.

Table 4.16. The CLSC-PIRP results

N_c	T	*CLSC-PIRP Approach*	
		Objective Value	CPU Time
20	**5**	239310	46
15	**10**	1213158	43217
10	**5**	592490	21538
20	**5**	155928	144
20	**10**	996984	43256
5	**10**	1015744	684
10	**10**	729038	380
15	**5**	898019	43200
10	**5**	473646	3274
15	**5**	1954518	8937
20	**10**	1137637	5591
5	**5**	245951	3
5	**5**	249008	4
10	**10**	447154	43231
15	**10**	2391846	43200
5	**10**	641226	484
Average		**836353**	**16074**

Main effects of number of periods and nodes on the CLSC-PIRP objectives are depicted in Figure 4.19. Increasing number of periods effected to the objective function values too much. Average objective value leaped about sixty thousands to above one million. According to increasing number of nodes, when the number of was selected as fifteen, the objective function reached the peak level. This can be caused regarding random generated cost parameters.

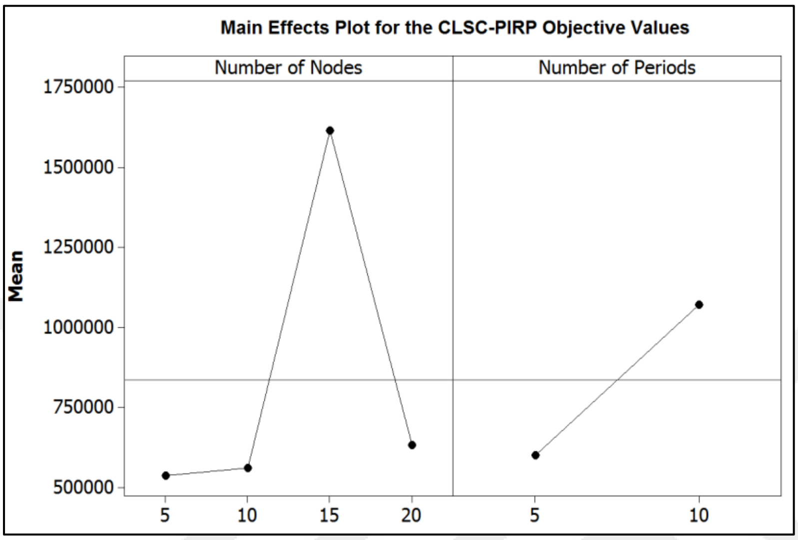


Figure 4.19. Effects of number of nodes and periods on the CLSC-PIRP objective values

Main effects of number of periods and nodes on the CLSC-PIRP CPU time are depicted in Figure 4.20. Increasing number of periods was not effect to the CPU times too much. The pattern of the graph is similar for objective results that is mentioned before.

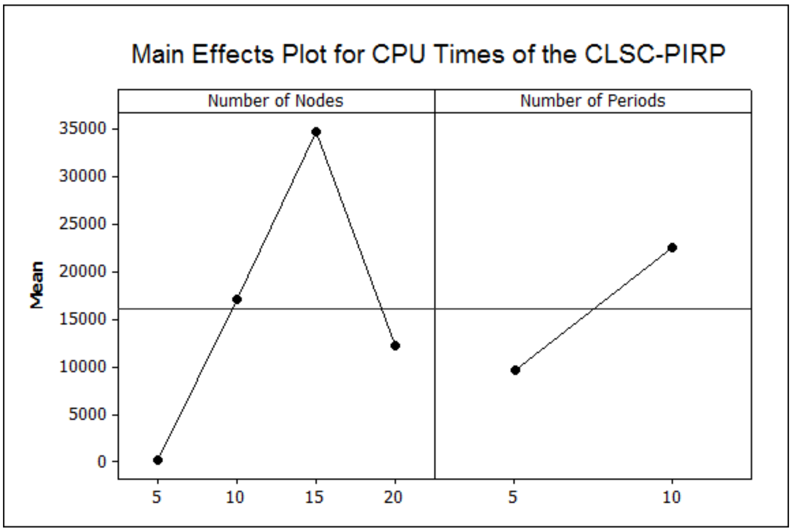


Figure 4.20. Effects of number of nodes and periods on the CLSC-PIRP solution times

Interactions of number of periods and nodes on the CLSC-PIRP solution time are illustrated in Figure 4.21. As the number of nodes and periods increase, we observe an increase in CPU time. Particularly, when the number of nodes is increased to twenty, the number of periods affects the solution time sophisticatedly. However, when the number of node is low, the increment in the number of periods does not affect CPU time, since the number of binary variables and constraints increase at the high level of the number of nodes.

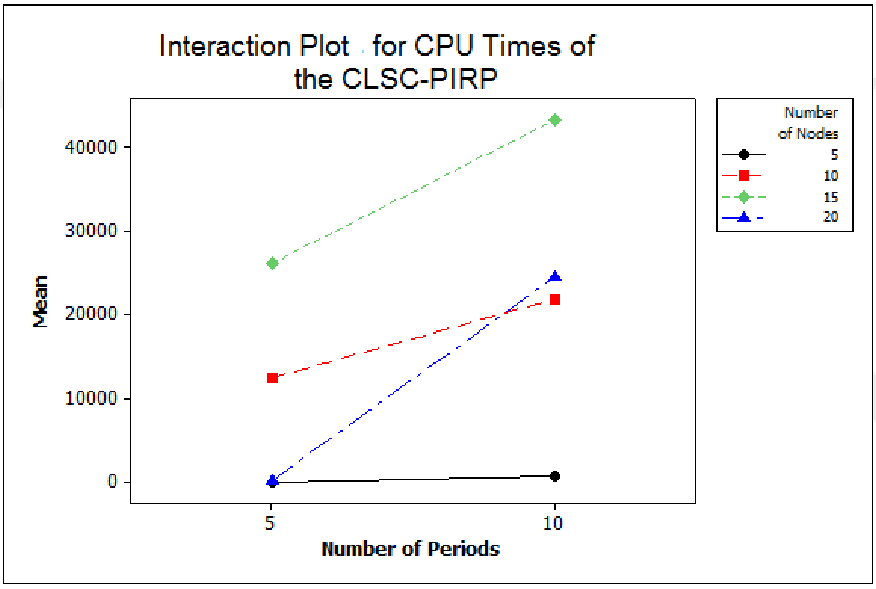


Figure 4.21. Interactions between number of nodes and periods on the CLSC-PIRP solution times

4.5.2. The two-stage approach results

The results obtained from two-stage approach problem is shown Table 4.17. Total chain's operational costs are calculated from the sum of both forward (FSP) and backward (BSP) problem results. It can be concluded from this table, overall chain costs increased when the number of nodes and periods were increased similarly CPU time.

Table 4.17. Two stage approach results

N_c	*T*	*Two-stage Approach*			
		FSP Objective Value	BSP Objective Value	Total Chain Objective Value	CPU Time
20	**5**	76291	167926	244217	39
15	**10**	264894	996801	1261695	17998
10	**5**	167008	602180	769188	16162
20	**5**	64393	91536	155928	97
20	**10**	269129	747070	1016199	48674
5	**10**	426498	638469	1064968	18623
10	**10**	44589	1302483	1347072	11
15	**5**	226597	684206	910803	18629
10	**5**	83505	494872	578377	162
15	**5**	176144	1964381	2140525	10064
20	**10**	346443	1302809	1649252	45904
5	**5**	18105	258773	276878	2
5	**5**	151324	110889	262213	17
10	**10**	157522	347886	505408	51342
15	**10**	354738	3091153	3445891	86401
5	**10**	356511	340299	696811	1789

Main effects of number of periods and nodes on the two-stage approach objectives are illustrated in Figure 4.22. The pattern of two stage approach is very similar to the CLSC-PIRP. Increasing the number of periods has influenced to the objective function values too much. When the number of is selected as fifteen, the objective function reaches the peak level. Only when the fifteen nodes are considered, the objective value occurs above the average value.

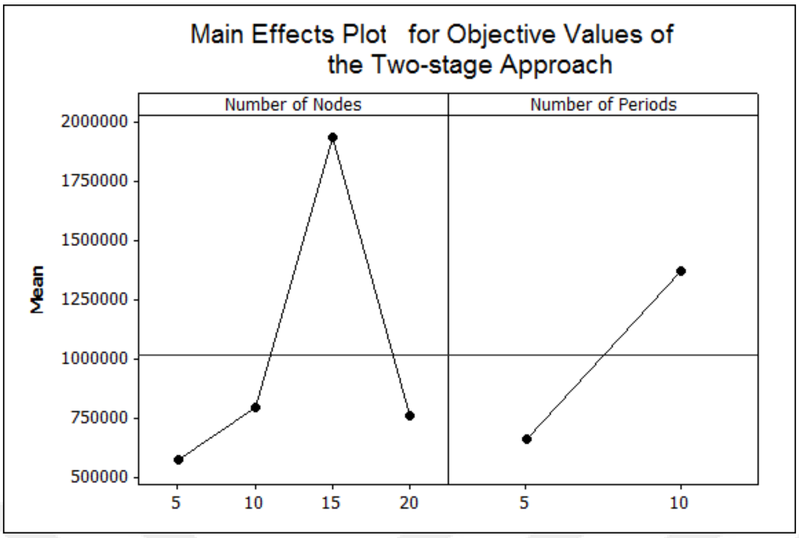


Figure 4.22. Effects of number of nodes and periods on the two-stage approach objective values

Main effects of number of periods and nodes on the two-stage approach CPU time are depicted in Figure 4.23. Increasing both of number of periods and nodes affected to the CPU time too much. It can be concluded from this figure, CLSC-PIRP is more robust regarding two-stage approach regarding these test instances.

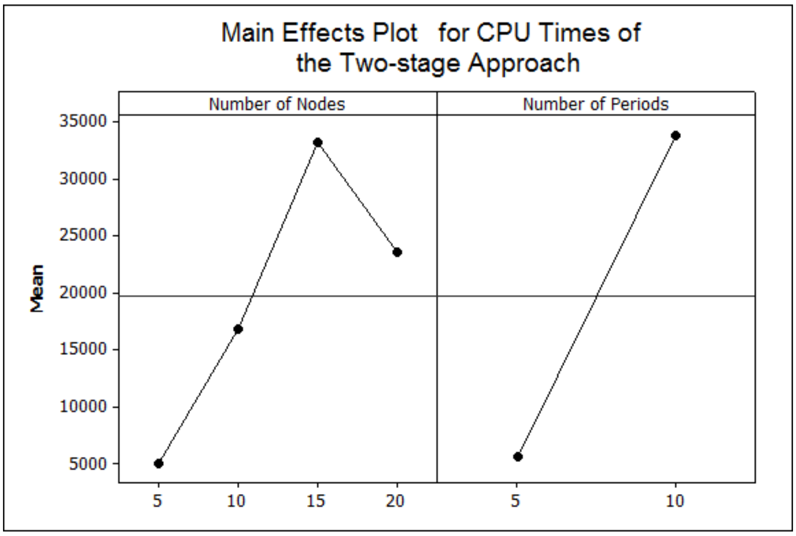


Figure 4.23. Effects of number of nodes and periods on the two-stage approach solution times

Interactions of number of periods and nodes on the two-stage approach solution time are illustrated in Figure 4.24. As the number of nodes and periods increase, we observe an increase in CPU time. Moreover, the effect of increasing the number of periods is quite higher increment in CPU time when the number of nodes increases, since the number of binary variables and constraints increase at the high level of the number of nodes.

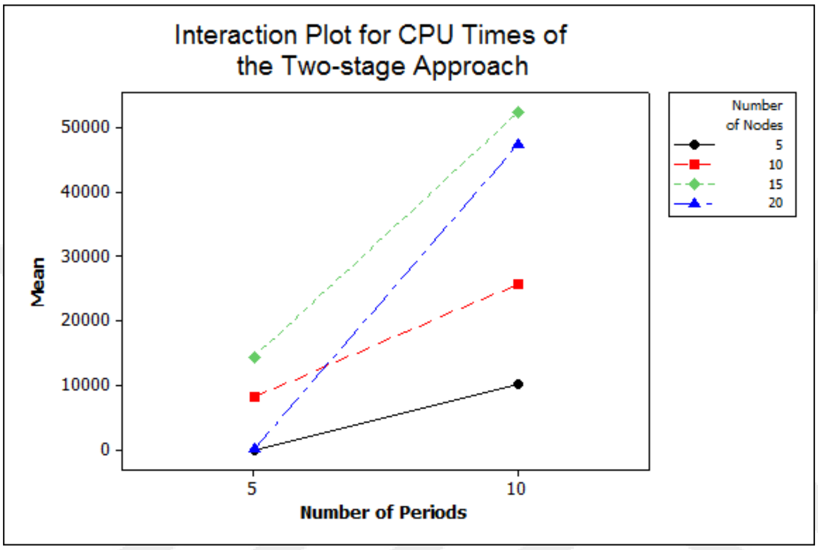


Figure 4.24. Interactions between number of nodes and periods on the two-stage approach solution times

4.5.3. Proposed Decomposition Heuristic Results

The results obtained from the proposed decomposition heuristic approach is shown Table 4.18. It can be concluded from this table, average solution time occurs about seven minutes. CPU time increased when the problem gets complicated.

Table 4.18. Proposed decomposition heuristic results

N_c	T	*Proposed Decomposition Heuristic Results*	
		Objective Value	CPU Time
20	**5**	264518	29
15	**10**	1300380	842
10	**5**	626733	135
20	**5**	168081	65
20	**10**	1091453	1669
5	**10**	1070640	33

Table 4.18. Proposed decomposition heuristic results (continued)

N_c	T	*Proposed Decomposition Heuristic Results*	
		Objective Value	CPU Time
10	**10**	781252	11
15	**5**	939431	118
10	**5**	505809	81
15	**5**	1998077	284
20	**10**	1189740	1366
5	**5**	248801	15
5	**5**	256021	17
10	**10**	488185	100
15	**10**	2510590	1694
5	**10**	690819	46
Average		**891908**	**407**

Main effects of number of periods and nodes on the proposed decomposition heuristic objectives are illustrated in Figure 4.25. This graph has similar pattern to the CLSC-PIRP and two-stage approaches objective graphs. This means all of the approaches are affected by number of nodes and periods similarly.

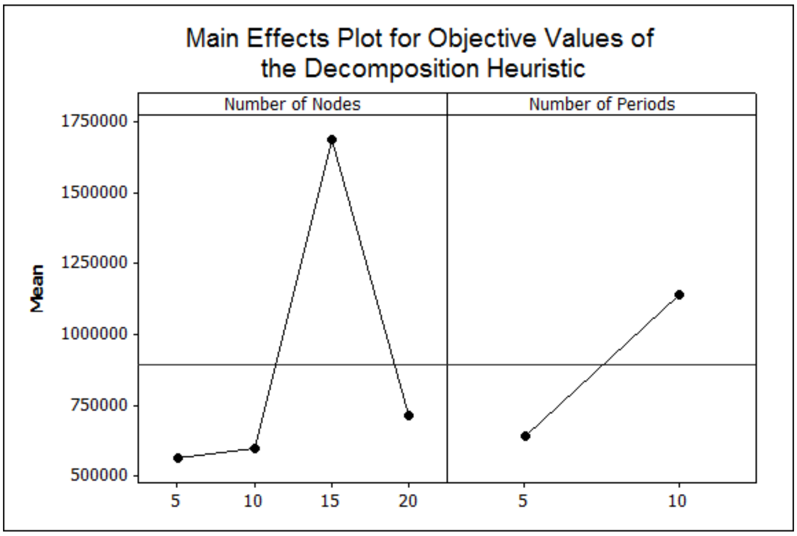


Figure 4.25. Effects of number of nodes and periods on the proposed decomposition heuristic objective values

Main effects of number of periods and nodes on the CPU time of the proposed decomposition heuristic are depicted in Figure 4.26. Proposed decomposition heuristic reacted the number of periods too rapidly, however the time values were much better than other approaches. When the number of nodes are increased, solution time increases too. But there are few differences after the number of nodes equals to fifteen.

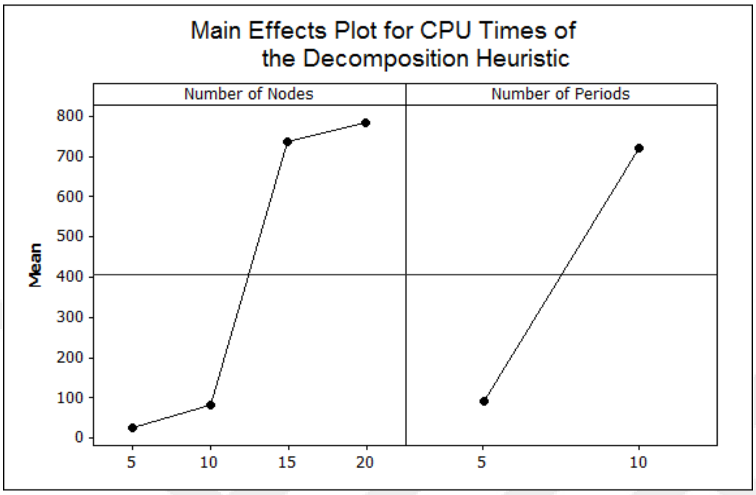


Figure 4.26. Effects of number of nodes and periods on the proposed decomposition heuristic solution times

Interactions of number of periods and nodes on the proposed decomposition heuristic solution time are illustrated in Figure 4.27. As the number of nodes is equals more than ten and the number of periods increases, we observe an increase in CPU time. The number of variables and constraints in the heuristic's evaluation model increase at the high level of the number of nodes; therefore, CPU time increases.

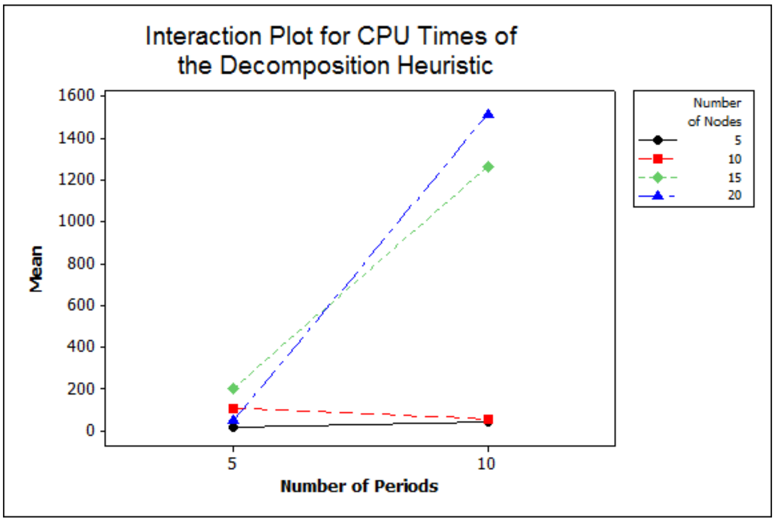


Figure 4.27. Interactions between number of nodes and periods on the proposed decomposition heuristic solution times

4.6. Comparison of the Methods

Table 4.19 summarizes the comparison between the CLSC-PIRP results and two-stage approach results. Results show that with using CLSC-PIRP approach operational costs can be decreased 18.07 percent on average. Furthermore, CLSC-PIRP solution has much less CPU time than two-stage approach. This has caused that solving vehicle routing problem twice increased solution time rapidly. Therefore, CLSC-PIRP approach is more beneficial than two-stage approach. Two-stage approach has less solution time than CLSC-PIRP only few cases. However, this is negligible. By integrating forward and backward production, inventory, distribution and routing decisions not only the total cost can be decreased about 0 to 85 percent but also it may be taken less CPU time.

Table 4.19. Comparison of mathematical modeling approaches results

N_c	*T*	*CLSC-PIRP Approach*		*Two-stage Approach*		*Difference (%)*	
		Objective Value	CPU Time	Total Objective Value	CPU Time	Objective Value	CPU Time
20	5	239310	46	244217	39	2.05	-15.59
15	10	1213158	43217	1261695	17998	4.00	-58.35
10	5	592490	21538	769188	16162	29.82	-24.96
20	5	155928	144	155928	97	0.00	-32.80
20	10	996984	43256	1016199	48674	1.93	12.53
5	10	1015744	684	1064968	18623	4.85	2623.69
10	10	729038	380	1347072	11	84.77	-97.11
15	5	898019	43200	910803	18629	1.42	-56.88
10	5	473646	3274	578377	162	22.11	-95.05
15	5	1954518	8937	2140525	10064	9.52	12.61
20	10	1137637	5591	1649252	45904	44.97	720.98
5	5	245951	3	276878	2	12.57	-43.22
5	5	249008	4	262213	17	5.30	303.54
10	10	447154	43231	505408	51342	13.03	18.76
15	10	2391846	43200	3445891	86401	44.07	100.00
5	10	641226	484	696811	1789	8.67	269.78
Average		**836353**	**16074**	**1020339**	**19745**	**18.07**	**227.37**

Table 4.20 summarizes the comparison between the CLSC-PIRP results and proposed decomposition heuristic results. Results show that with using CLSC-PIRP approach operational costs can be decreased 6.09 percent on average. Nevertheless, CLSC-PIRP solution needs much more CPU time than proposed decomposition heuristic method. The solution time can be decreased about 36 percent by using the heuristic approach. Therefore, proposed decomposition heuristic approach may reach to good solutions more rapidly and few amount of excess cost than CLSC-PIRP. By using proposed decomposition heuristic method, overall costs can be exceed about 1 to 10 percent. However, the solution time decrases too much. Therefore, the heuristic method can easily find near optimal solutions when the problem is complicated.

Table 4.20. Comparison of the CLSC-PIRP and proposed decompositon heuristic approaches results

N_c	T	*CLSC-PIRP Approach*		*Decomposition Heuristic*		*Difference (%)*	
		Objective Value	CPU Time	Total Objective Value	CPU Time	Objective Value	CPU Time
20	5	239310	46	264518	29	10.53	-37.18
15	10	1213158	43217	1300380	842	7.19	-98.05
10	5	592490	21538	626733	135	5.78	-99.37
20	5	155928	144	168081	65	7.79	-54.41
20	10	996984	43256	1091453	1669	9.48	-96.14
5	10	1015744	684	1070640	33	5.40	-95.15
10	10	729038	380	781252	11	7.16	-97.19
15	5	898019	43200	939431	118	4.61	-99.73
10	5	473646	3274	505809	81	6.79	-97.54
15	5	1954518	8937	1998077	284	2.23	-96.83
20	10	1137637	5591	1189740	1366	4.58	-75.56
5	5	245951	3	248801	15	1.16	344.39
5	5	249008	4	256021	17	2.82	312.29
10	10	447154	43231	488185	100	9.18	-99.77
15	10	2391846	43200	2510590	1694	4.96	-96.08
5	10	641226	484	690819	46	7.73	-90.42
Average		**836353**	**16074**	**891908**	**407**	**6.09**	**-36.05**

Figure 4.28 and 4.29 show the comparison of the methods' objective values and solution times regarding number of nodes and periods. According to the results of the changing number of nodes, the two-stage approach deviates from other methods increasingly when the number of nodes is increased (Figure 4.28). However, proposed decomposition heuristic and the CLSC-PIRP results are very close for almost all cases. According to the CPU times, proposed decomposition heuristic is much more effective than others. It seems the CLSC-PIRP and the two-stage approach are not significantly different from each other regarding CPU times.

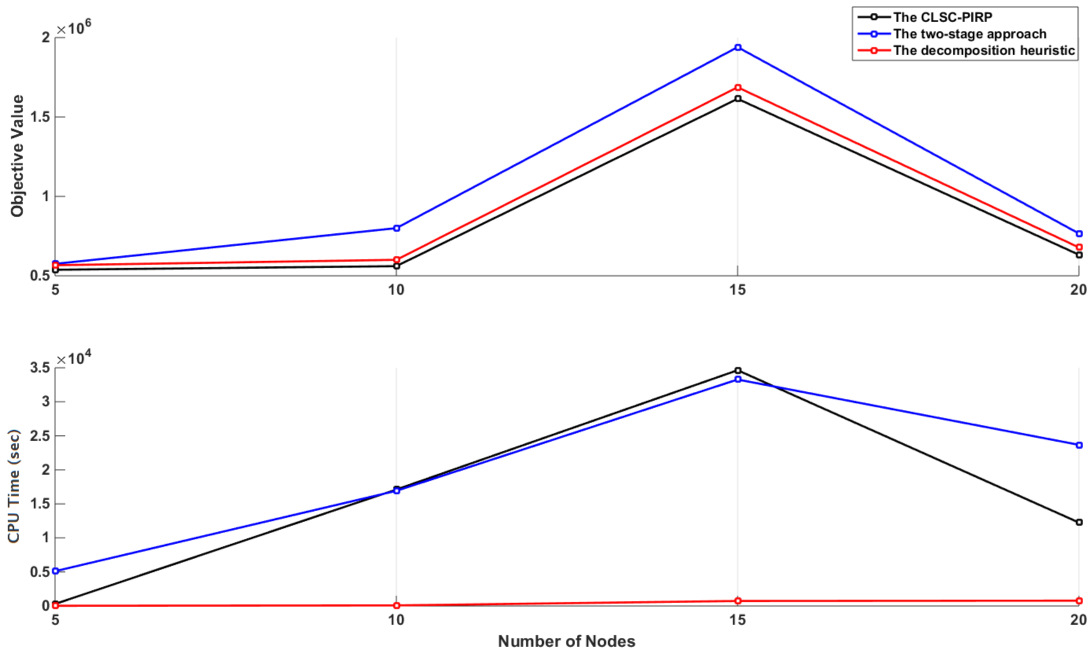


Figure 4.28. Comparison of the methods according to number of nodes

According to results of changing the number of periods that are depicted in Figure 4.29, the CLSC-PIRP and proposed decomposition heuristic appear to closely by the objective values. The devation from the optimal solution increased for the two-stage approach, when the number of periods increased. This result is similar for CPU time. The CLSC-PIRP and the two-stage approaches needed much more CPU time, when the number of periods increased. However, proposed decomposition approach's solution time seems still stable.

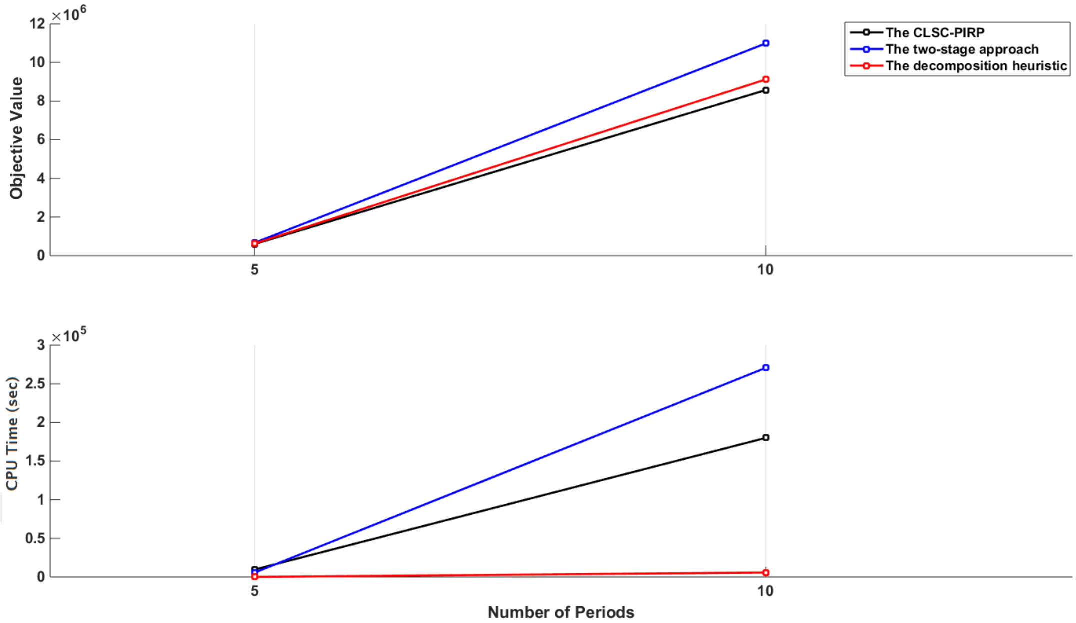


Figure 4.29. Comparison of the methods according to number of periods

4.7. Large Scale Problems

As mentioned in section 4.6, proposed decomposition heuristic method can provide near optimal solutions, when the problem is not solved optimally. In order to show the robustness of proposed decomposition heuristic the number of nodes varies from 10 to 100. Figure 4.30 shows the changes on solution time regarding number of nodes. The test problem is generated randomly, number of periods is set to five days and the maximum number of trucks is set to ten. The cost parameters (preparation costs, holding costs, transportation costs) are generated randomly and same for each instance. Proposed decomposition method searches the solution area randomly. For this reason, each problem is solved five times. According to Figure 4.30, solution time is still reasonable, therefore proposed decomposition heuristic has an ability to solve large scale problems. When the number of nodes was increased, the solution time also increased. The minimium average solution time took about ten seconds as the maximum average solution time took about eigth hundred seconds. It is observed that proposed decomposition method solved the test instances with a slight difference between replications.

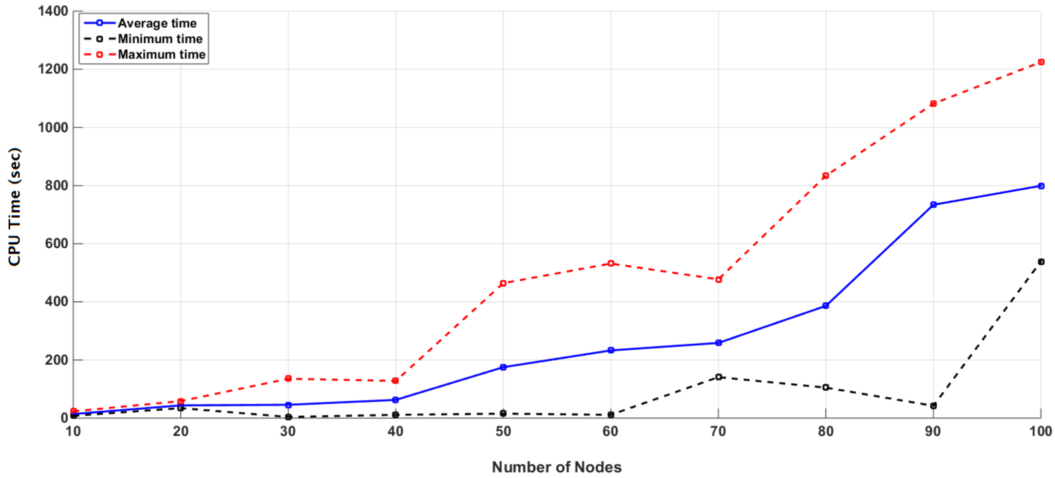


Figure 4.30. Solution time of proposed decomposition heuristic regarding number of nodes

According to the results obtained for different number of nodes, the changing on total costs is depicted in Figure 4.31. As mentioned before, proposed decomposition heuristic was run five times for each test instance in order to examine the changes. The random test parameters are used; accordingly, the total cost values changes from instance to instances. However, it appears the average, minimum and maximum total costs quite close regarding all test instances. Only the slight difference occurred on when the number of nodes increased to one hundred.

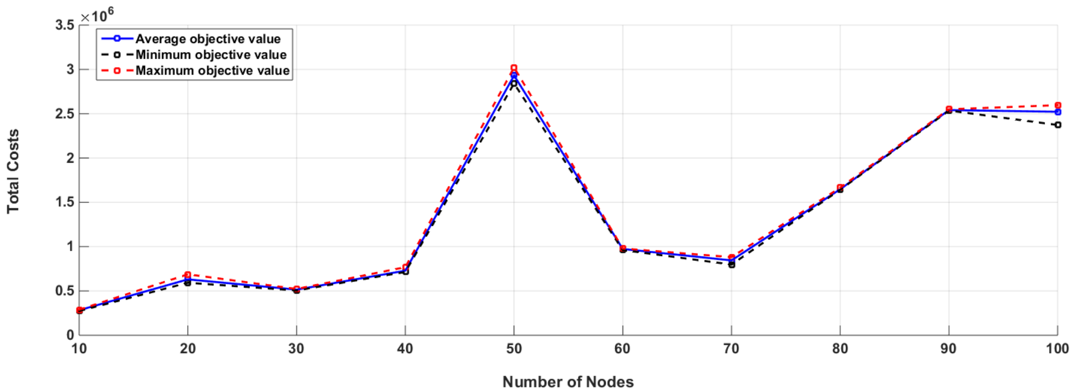


Figure 4.31. Objective values (total costs) regarding number of nodes

In addition to total cost values, the gap between average cost value and best found cost value is analyzed in Figure 4.32. The maximum gap was occurred about seven percent when the number of nodes equals to twenty and one hundred.

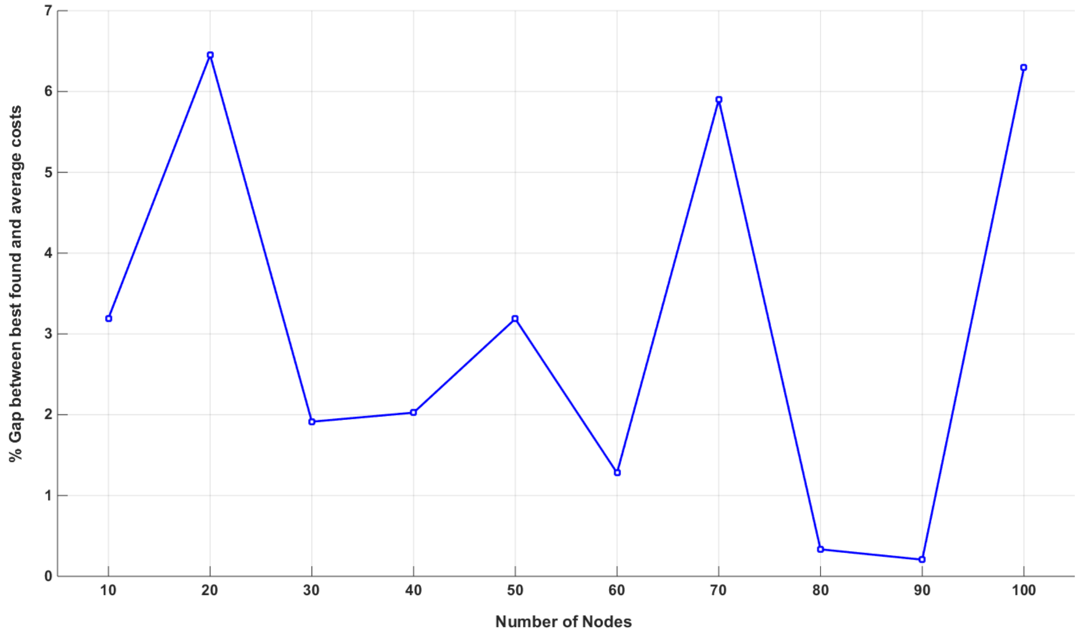


Figure 4.32. Gap between average solutions and best found regarding number of nodes

As a result of observations of figures, it seems that proposed decomposition heuristic has a good ability to solve the medium and large scale instances. The problem is complicated when the number of nodes increased; however, the CPU time is still reasonable. In addition to lower computational time, proposed decomposition heuristic method solved the problem within a slight difference between replications. It can be concluded from these results, proposed decomposition heuristic method is a convenient way to solve large scale instances instead of exact methods (MIP).

5. CONCLUSION

5.1. Summary

In this study, the coordinated production, inventory, distribution and routing problem is considered. The main objective of this study is to show the effects of considering both forward and backward flows of a closed loop supply chain on the problem. According to limited literature review, the study is the first attempt on this issue.

The problem is called as the Coordinated Production, Inventory, Distribution and Routing Problem on Closed Loop Supply Chains (CLSC-PIRP) and it is formulated mathematically.

Various solution methodologies can be applied, therefore, in this study, integer programming approach and an heuristic method are implemented in order to solve CLSC-PIRP. The heuristic method is based on simulated annealing and linear programming approaches. GAMS optimization software is used for integer and linear programming methods. The heuristic is coded via MATLAB software package.

A case study for a fats oil (margarine) closed loop supply chain is conducted. Problem planned for fifteen days is solved via integer programming approach. Furthermore, for real life applications, a graphical user interface that provides user-friendly usage is built. The GUI has some capabilities such as importing Microsoft Excel data and solving the CLSC-PIRP by optimally or the decomposed heuristic approach. Moreover, results are illustrated based on graphic and they can be saved in hard drive.

The model has some parameters that are controlled by user. Determining these parameters may be vital regarding the model's results. For this aim, sensitivity analysis is applied to measure the model whether is sensitive or not. The model's behaviors according to different scenarios are evaluated by created scenario analysis.

In order to evaluate the effects of coordination, random test instances are generated and solved. The forward and backward sub-problems are solved hierarchically by the method called as two stage approach. The CLSC-PIRP and two stage approach are compared by the results obtained from the random instances.

5.2. Conclusion

In this section, the results obtained from the study are given as follows:

- The CLSC-PIRP is proposed for coordinating production, inventory, distribution and routing decisions.
- The closed loop supply chain that is considered has only two reverse logistic operations; recycling or disposal
- Singe manufacturer, single recycler, single product and multi period problem is analyzed.
- Due to computational complexity of the CLSC-PIRP, the number of decision variables and constraints are rapidly increased when the number of periods, trucks and nodes are increased. This means that the proposed problem may not be solved in a reasonable time limit.
- Sensitivity analysis is applied to the generated random test problem. According to results, the model is generally robust on the changes in objective coefficients. The main observation from this analysis, the problem has strong behavior on estimated parameters value.
- This problem is motivated from the regional fats oil supply chain. Therefore, a case study is conducted from this chain and results are given. The case problem is solved by both CLSC-PIRP and two stage approach. And results show that the chain may save about ten percent in overall supply chain operational costs.
- As mentioned before, the problem may not be solved optimally when the number of periods, trucks and nodes are increased. For this reason, the decomposition heuristic is proposed in order to solve large scale instances.
- Proposed decomposition heuristic decomposes the problem into two parts regarding routing and other decisions. The method is based on simulated

annealing approach. The tours are built by modified savings algorithm and other decisions are made by a linear programming model.

- The user defined parameters of the simulated annealing method are set by evaluating different levels of each parameter.
- Different scenarios are applied in order to compare the CLSC-PIRP, the two-stage approach and proposed decomposition heuristic method regarding solution time and total chain costs.
- According to the results, the first main examination is that, the total chain costs of the two-stage approach (FSP and BSP) is not nearby to the total chain costs of the CLSC-PIRP. In the two-stage approach, FSP and BSP are linked together, hovewer forward and backward decisions are made seperately instead of simultaneously. The gap between the total costs is about twenty percent on average regarding case study and test instances results. For this reason, the CLSC-PIRP has a great ability to minimize the total cost of the chain.
- The second observation, it seems the results obtained from proposed decomposition heuristic and the CLSC-PIRP are certainly close, therefore proposed decomposition heuristic is an alternative way on this issue. The gap between the total costs of proposed decomposition heuristic and the CLSC-PIRP is about six percent, hovewer solution time is less about thirty five percent on proposed decomposition heuristic.
- Finally, the CLSC-PIRP has a favorible way to solve the coordinated production, inventory, distribution and routing problem on medium and small instances. Proposed decomposition heuristic has a great potential to find near optimal solutions in a fewer time on large scale instances.

5.3. Future Suggestions

As an extension for future research, some suggestions are made as follows:

- The problem characteristic can be expanded. The problem is considered as a single product environment. Multi-product version of the problem can be studied. Particularly, related products can be thought such as milk and cheese. The returned milks can be used in cheese production.
- Taken into consideration of forward supply chain, the CLSC-PIRP problem can be extended to multi-production plant environment. Customers can be included into the problem.
- When the backward supply chain is thought, the problem can be modeled for different reverse logistic activities such as the remanufacturing option.
- Each collected product may have different condition. This implies collection costs vary to collected product. Demands are also assumed that known in advance. Demands of new and collected product can be considered as uncertain.
- According to solution methods, proposed decomposition heuristic is proposed for solving large instances. Other heuristic methods can be studied in order to find solutions more rapidly.
- The problem may be designed as agent based simulation environment in order to take into consideration of more real life aspects.

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BIOGRAPHY

Yusuf KUVVETLI holds an MSc and a BS degree in Industrial Engineering Department from Cukurova University in 2008 and 2010. He started to PhD studies in Industrial Engineering Department from Cukurova University in 2011. He has worked as a research assistant in the Industrial Engineering Department at Cukurova University since 2011. His current research interests are; supply chains management, reverse logistics and closed loop supply chains, assembly lines, artificial intelligence and computer science issues.

APPENDIX

Appendix 1 – GAMS Model of the CLSC-PIRP

```
scalar starttime; starttime = jnow;

$include data.txt

positive variables      pnew(t) new product quantity on period t
        prm(t) remanufactured product quantity on period t
        p(t) production quantity on period t
        I(n,t) inventory quantity for node i on period t
        Irm(n,t) used product inventory quantity for node i on period t
        Q(n,k,t) new product transportation quantity
        Qrm(n,k,t) used product transportation quantity
        X(n,r,k,t) transportation quantity between n and r
        Xrm(n,r,k,t) transportation quantity between n and r;
binary variables
        Y(t) if new product produced on period t 1 otherwise 0
        Yrm(t) if remanufactured product produced on period t 1 otherwise 0
        Z(n,r,k,t) transportation connection binary
        U(k,t) vehicle usage binary;
variables zmin;

Equations
        obj    objective function
        inv(t) inventory balance (production)
        inv2(t) inventory balance (remanufacturing)
        inv3(n,t) new inventory balance consumption
        inv4(n,t) return inventory balance consumption
        cap(n,r,k,t) vehicle capacity
        quan(r,k,t) vehicle quantity
        quan2(t) vehicle quantity2
        quan3(r,k,t) vehicle quantity3
        quan4(t) vehicle quantity4
        rou2(k,t) route length
        rou3(k,t) route constraints1
        rou4(n,k,t) route constraints2
        rou5(k,t) route constraints3
        pro1(t) production capacity
        pro2(t) remanufacturing capacity
        pro3(t) remanufacturing capacity
        pro4(t) remanufacturing capacity
        invc(n,t) inventory capacity
        invc2(n,t) inventory capacity
        invc3(n) inventory capacity
        invc4(n) inventory capacity
        production production
        production2 production;
```

```
obj..    zmin =e= sum(t$(ord(t) >= 2), Yrm(t)*srm+sum(n, Irm(n,t)*hrm +
sum(r$(ord(n) ne ord(r)),sum(k,Z(n,r,k,t)*l(n,r)*ctr))))
             +sum(t$(ord(t)>=2), sum(k, U(k,t)*f)+Y(t)*s+sum(n, I(n,t)*h )
+pur(t)*pnew(t)+sum(n,sum(k,qrm(n,k,t)*purrm(t))));


inv(t)$(ord(t)>=2).. I('1',t-1)+p(t)-I('1',t)=e=sum(n$(ord(n)>=2),sum(k,Q(n,k,t)));
inv2(t)$(ord(t)>=2).. IRM('1',t-1)-prm(t)-IRM('1',t)=e=sum(n$(ord(n)>=2),sum(k,-
QRM(n,k,t)));
inv3(n,t)$(ord(t)>=2 and ord(n)>=2).. sum(k, Q(n,k,t))+I(n,t-1)-I(n,t)-d(n,t)=e=0;
inv4(n,t)$(ord(t)>=2 and ord(n)>=2).. sum(k, -QRM(n,k,t))+IRM(n,t-1)-
IRM(n,t)+drm(n,t)=e=0;

quan(r,k,t)$(ord(t)>=2 and ord(r)>=2).. sum(n$(ord(n) ne ord(r)), X(n,r,k,t))-
sum(j$(ord(j) ne ord(r)), X(r,j,k,t))=e=Q(r,k,t);
quan3(r,k,t)$(ord(t)>=2 and ord(r)>=2).. sum(n$(ord(n) ne ord(r)), Xrm(n,r,k,t))-
sum(j$(ord(j) ne ord(r)), Xrm(r,j,k,t))=e=-Qrm(r,k,t);
quan2(t)$(ord(t)>=2).. sum(r$(ord(r)>=2), sum(k, X('1',r,k,t)))-sum(r$(ord(r)>=2),
sum(k, X(r,'1',k,t)))=e=sum(r,sum(k,Q(r,k,t)));
quan4(t)$(ord(t)>=2).. sum(r$(ord(r)>=2), sum(k, Xrm('1',r,k,t)))-sum(r$(ord(r)>=2),
sum(k, Xrm(r,'1',k,t)))=e=sum(r,sum(k,-Qrm(r,k,t)));

cap(n,r,k,t)$((ord(t)>=2) and (ord(n) ne ord(r)))..
X(n,r,k,t)+Xrm(n,r,k,t)=l=C*Z(n,r,k,t);
rou2(k,t)$(ord(t)>=2)..     sum(n$(ord(n)>=2), Z('1',n,k,t))=g=1*U(k,t);
rou5(k,t)$(ord(t)>=2)..     sum(n$(ord(n)>=2), Z(n,'1',k,t))=g=1*U(k,t);
rou3(k,t)$(ord(t)>=2)..     sum(n, sum(r$(ord(n) ne ord(r)),
Z(n,r,k,t)*l(n,r)))=l=Len*U(k,t);
rou4(n,k,t)$(ord(t)>=2)..   sum(r$(ord(n) ne ord(r)), Z(r,n,k,t))-sum(j$(ord(j) ne
ord(n)), Z(n,j,k,t))=e=0;
pro1(t)$(ord(t)>=2)..       p(t)=l=B*Y(t);
pro2(t)$(ord(t)>=2)..       prm(t)=l=Brm*Yrm(t);
pro3(t)$(ord(t)>=2)..       prm(t)=l=beta*P(t);
pro4(t)$(ord(t)>=2)..       p(t)=l=alfa*(pnew(t)+prm(t));
invc(n,t)$(ord(t)>=2)..       I(n,t)=l=Imax(n);
invc2(n,t)$(ord(t)>=2)..       Irm(n,t)=l=Imaxrm(n);
invc3(n)..     I(n,'1')=e=0;
invc4(n)..     Irm(n,'1')=e=0;
production..  Y('1')=e=0;
production2..  Yrm('1')=e=0;

option mip=cplex;

Model clsc /all/;
clsc.OptCA=0.00000001;
```

```
clsc.OptCR=0.0001;
option ResLim=43200;

Solve clsc using mip minimizing zmin;

scalar elapsed; elapsed = (jnow - starttime)*24*3600;
display elapsed;
display zmin.l, q.l, qrm.l, p.l, prm.l, I.l, Irm.l, Z.l, X.l, U.l;
```

Appendix 2 – GAMS Model of Solution Evaluation

```
scalar starttime; starttime = jnow;

$include data.txt

parameters
Z(n,r,k,t) transportation connection binary
U(k,t) vehicle usage binary
pen penalty
$GDXIN MtoG.gdx
$LOAD Z,U,pen
$GDXIN
;
display Z, U;

positive variables      pnew(t) new product quantity on period t
        prm(t) remanufactured product quantity on period t
        p(t) production quantity on period t
        I(n,t) inventory quantity for node i on period t
        Irm(n,t) used product inventory quantity for node i on period t
        Q(n,k,t) new product transportation quantity
        Qrm(n,k,t) used product transportation quantity
        X(n,r,k,t) transportation quantity between n and r
        Xrm(n,r,k,t) transportation quantity between n and r;
positive variables
        v1(n,t) inventory quantity for node i on period t
        vrm1(n,t) used product inventory quantity for node i on period t
        v2(n,t) inventory quantity for node i on period t
        vrm2(n,t) used product inventory quantity for node i on period t
;
binary variables
        Y(t) if new product produced on period t 1 otherwise 0
        Yrm(t) if remanufactured product produced on period t 1 otherwise 0
variables zmin;

Equations
        obj    objective function
        inv(t) inventory balance (production)
        inv2(t) inventory balance (remanufacturing)
        inv3(n,t) inventory balance
        inv4(n,t) inventory balance
        quan(r,k,t) vehicle capacity
        quan2(t) vehicle capacity
        quan3(r,k,t) vehicle capacity
        quan4(t) vehicle capacity
```

```
        cap(n,r,k,t)
        rou3(k,t)
        pro1(t) production capacity
        pro2(t) remanufacturing capacity
        pro3(t) remanufacturing capacity
        pro4(t) remanufacturing capacity
        invc(n,t) inventory capacity
        invc2(n,t) inventory capacity
        invc3(n) inventory capacity
        invc4(n) inventory capacity
        invc5(n,t)
        invc6(n,t)
        production production
        production2 production;

obj..     zmin =e= sum(t$(ord(t) >= 2), Yrm(t)*srm+sum(n, Irm(n,t)*hrm +
sum(r$(ord(n) ne ord(r)),sum(k,Z(n,r,k,t)*l(n,r)*ctr))))
              +sum(t$(ord(t)>=2), sum(k, U(k,t)*f)+Y(t)*s+sum(n, I(n,t)*h
)+pur(t)*pnew(t)+sum(n,sum(k,qrm(n,k,t)*purrm(t))))
+sum(n, sum(t$(ord(t)>=2), pen*(v1(n,t)+vrm1(n,t)+v2(n,t)+vrm2(n,t)) ));

inv(t)$(ord(t)>=2).. I('1',t-1)+p(t)-I('1',t)-
v1('1',t)+v2('1',t)=e=sum(n$(ord(n)>=2),sum(k,Q(n,k,t)));
inv2(t)$(ord(t)>=2).. IRM('1',t-1)-prm(t)-IRM('1',t)-
vrm1('1',t)+vrm2('1',t)=e=sum(n$(ord(n)>=2),sum(k,-QRM(n,k,t)));
inv3(n,t)$(ord(t)>=2 and ord(n)>=2).. sum(k, Q(n,k,t))+I(n,t-1)-I(n,t)-
v1(n,t)+v2(n,t)-d(n,t)=e=0;
inv4(n,t)$(ord(t)>=2 and ord(n)>=2).. sum(k, -QRM(n,k,t))+IRM(n,t-1)-IRM(n,t)-
vrm1(n,t)+vrm2(n,t)+drm(n,t)=e=0;

quan(r,k,t)$(ord(t)>=2 and ord(r)>=2).. sum(n$(ord(n) ne ord(r)), X(n,r,k,t))-
sum(j$(ord(j) ne ord(r)), X(r,j,k,t))=e=Q(r,k,t);
quan3(r,k,t)$(ord(t)>=2 and ord(r)>=2).. sum(n$(ord(n) ne ord(r)), Xrm(n,r,k,t))-
sum(j$(ord(j) ne ord(r)), Xrm(r,j,k,t))=e=-Qrm(r,k,t);
quan2(t)$(ord(t)>=2).. sum(r$(ord(r)>=2), sum(k, X('1',r,k,t)))-sum(r$(ord(r)>=2),
sum(k, X(r,'1',k,t)))=e=sum(r,sum(k,Q(r,k,t)));
quan4(t)$(ord(t)>=2).. sum(r$(ord(r)>=2), sum(k, Xrm('1',r,k,t)))-sum(r$(ord(r)>=2),
sum(k, Xrm(r,'1',k,t)))=e=sum(r,sum(k,-Qrm(r,k,t)));
rou3(k,t)$(ord(t)>=2)..     sum(n, sum(r$(ord(n) ne ord(r)),
Z(n,r,k,t)*l(n,r)))=l=Len*U(k,t);
cap(n,r,k,t)$((ord(t)>=2) and (ord(n) ne ord(r)))..
X(n,r,k,t)+Xrm(n,r,k,t)=l=C*Z(n,r,k,t);


pro1(t)$(ord(t)>=2)..          p(t)=l=B*Y(t);
pro2(t)$(ord(t)>=2)..          prm(t)=l=Brm*Yrm(t);
```

```
pro3(t)$(ord(t)>=2)..          prm(t)=l=beta*P(t);
pro4(t)$(ord(t)>=2)..          p(t)=l=alfa*(pnew(t)+prm(t));
invc(n,t)$(ord(t)>=2)..          I(n,t)=l=Imax(n);
invc2(n,t)$(ord(t)>=2)..          Irm(n,t)=l=Imaxrm(n);
invc5(n,t)$(ord(t)>=2)..          0=l=I(n,t);
invc6(n,t)$(ord(t)>=2)..          0=l=Irm(n,t);

invc3(n)..       I(n,'1')=e=0;
invc4(n)..       Irm(n,'1')=e=0;
production..  Y('1')=e=0;
production2..  Yrm('1')=e=0;

option mip=cplex;
Model clsc /all/;
Solve clsc using mip minimizing zmin;
scalar elapsed; elapsed = (jnow - starttime)*24*3600;
display elapsed;
```

Appendix 3 – Create Random Dataset Function

```
function [
d,drm,b,brm,Imax,Imaxrm,pur,purrm,C,f,h,hrm,ctr,s,srm,len
,beta,alfa,cx,cy,l,v,n,p ] = create_dataset( v,n,p,dr)

lr=2;
cr=2;
ir=2;
d=[zeros(1,p+1);randi(1000,n,p+1)];
del=round(p*dr)+1;
yy=1+randi(p,del,1);
for i=1:1:del
d(:,yy(i,1))=0;
end
drm=[zeros(1,p+1);randi(500,n,p+1)];
yy=1+randi(p,del,1);
for i=1:1:del
drm(:,yy(i,1))=0;
end
d(:,1)=0;
drm(:,1)=0;
Imax=1000+randi(500,n+1,1);
Imaxrm=1000+randi(500,n+1,1);
b=(sum(sum(d))+sum(Imax))*ir;
brm=(sum(sum(drm))+sum(Imaxrm))*ir;
pur=randi(15,p+1,1);
purrm=randi(15,p+1,1);
cx=[0;10+randi(500,n,1)];
cy=[0;10+randi(500,n,1)];
l=zeros(n+1,n+1);
for i=1:1:n+1
    for j=1:1:n+1
        l(i,j)=sqrt((cy(j,1)-cy(i,1))^2+(cx(j,1)-
cx(i,1))^2);
    end
end

C=(b+brm)/v*cr;
f=randi(1000,1,1);
h=randi(10,1,1);
hrm=randi(10,1,1);
ctr=randi(10,1,1);
s=randi(50000,1,1);
srm=randi(50000,1,1);
len=round(sum(l(:,3))*lr);
beta=max(0.2,rand());
```

```
alfa=max(0.2,rand()*2);

end
```

Appendix 4 – Detailed Sensitivity Analysis Results

f/c	s/h	srm/hrm	Obj.	Time	Prod. Day	Recy. Day	Distr. Day	Inv. Level	Return Inv. Level
10	1000	1000	298585.5	21.038	3	2	3	9410	8995
10	1000	100	280946.1	9.84	4	4	4	6998	7086
5	100	100	251237.1	116.691	5	5	5	6037	5164
1	10000	10000	584312	179.35	1	1	3	15581	15649
10	10000	10000	584474	276.37	2	1	3	15581	15649
5	100	10000	347477.1	504.409	4	1	4	6998	15649
5	1000	1000	298495.5	35.485	3	2	3	9410	8995
1	10000	1000	514423.5	67.625	3	2	3	9410	8995
1	100	1000	269675.1	42.685	4	2	4	6998	8995
10	10000	1000	514585.5	137.35	3	2	3	9410	8995
10	100	100	251387.1	21.211	5	5	5	6037	5164
10	100	1000	269891.1	10.025	4	2	4	6998	8995
10	100	10000	347597.1	45.966	4	1	4	6998	15649
1	100	10000	347381.1	606.34	4	1	4	6998	15649
5	10000	1000	514495.5	45.769	3	2	3	9410	8995
1	10000	100	501002.5	25.478	3	3	3	9410	8292
5	100	1000	269771.1	24.516	4	2	4	6998	8995
1	1000	10000	376129.5	3867.099	3	1	3	9410	15649
10	10000	100	501164.5	42.317	3	3	3	9410	8292
10	1000	10000	376291.5	1882.142	3	1	3	9410	15649
1	1000	1000	298423.5	20.566	3	2	3	9410	8995
5	10000	100	501074.5	26.054	3	3	3	9410	8292
1	100	100	251117.1	76.312	5	5	5	6037	5164
1	1000	100	280730.1	9.317	4	4	4	6998	7086
5	1000	10000	376201.5	2345.287	3	1	3	9410	15649
5	10000	10000	584384	244.182	2	1	3	15581	15649
5	1000	100	280826.1	22.885	4	4	4	6998	7086