

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**ADVANCED SCENARIO PLANNING: NEW APPROACHES FOR  
DEVELOPING, EVALUATING, AND SELECTING SCENARIOS WITH  
APPLICATIONS**



**Ph.D. THESIS**

**Özgür YANMAZ**

**Department of Industrial Engineering**

**Industrial Engineering Programme**

**OCTOBER 2024**



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**Özgür YANMAZ  
(507162125)**

**Department of Industrial Engineering**

**Industrial Engineering Programme**

**Thesis Advisor: Assoc. Prof. Dr. Umut ASAN**

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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

**İLERİ SENARYO PLANLAMA: SENARYOLARIN GELİŞTİRİLMESİ,  
DEĞERLENDİRİLMESİ VE SEÇİLMESİ İÇİN YENİ YAKLAŞIMLAR VE  
UYGULAMALARI**

**DOKTORA TEZİ**

**Özgür YANMAZ  
(507162125)**

**Endüstri Mühendisliği Anabilim Dalı**

**Endüstri Mühendisliği Programı**

**Tez Danışmanı: Doç. Dr. Umut ASAN**

**EKİM 2024**



Özgür YANMAZ, a Ph.D. student of İTÜ Graduate School student ID 507162125, successfully defended the thesis/dissertation entitled “ADVANCED SCENARIO PLANNING: NEW APPROACHES FOR DEVELOPING, EVALUATING, AND SELECTING SCENARIOS WITH APPLICATIONS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

**Thesis Advisor :**     **Assoc. Prof. Dr. Umut ASAN** .....  
İstanbul Technical University

**Jury Members :**     **Asst. Prof. Dr. Cafer Erhan BOZDAĞ** .....  
İstanbul Technical University

**Asst. Prof. Dr. Umman Mahir YILDIRIM**.....  
İstanbul Bilgi University

**Prof. Dr. Seçkin POLAT** .....  
İstanbul Technical University

**Assoc. Prof. Dr. Sait GÜL** .....  
Bahçeşehir University

**Date of Submission : 29 August 2024**

**Date of Defense : 24 October 2024**





*To unwritten scripts...*



## FOREWORD

I would like to extend my deepest gratitude to those who have significantly contributed to the completion of this dissertation. First of all, I am profoundly grateful to my advisor, Assoc. Prof. Dr. Umut ASAN, for his guidance and support. I also wish to express my sincere thanks to the members of my committee, Assist. Prof. Dr. Erhan BOZDAĞ and Assist. Prof. Dr. Mahir YILDIRIM. Their insightful feedback and constructive criticism greatly enhanced the quality of this research.

Additionally, I am deeply thankful to my wife, Çiğdem, for her patience and encouragement throughout this process. Her support and understanding have been a constant source of strength and motivation, helping me to navigate the challenges and demands of this endeavor.

I am also grateful to my family for their continuous support and belief in me throughout my entire educational and personal journey. Their sacrifices and encouragement have been crucial in enabling me to achieve this milestone.

Finally, I would like to thank the Scientific and Technological Research Council of Turkey (TÜBİTAK) for their financial support (2211, 2214-A), which has significantly contributed to the completion of this dissertation.

August 2024

Özgür YANMAZ  
(Industrial Engineer)



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# **ADVANCED SCENARIO PLANNING: NEW APPROACHES FOR DEVELOPING, EVALUATING, AND SELECTING SCENARIOS WITH APPLICATIONS**

## **SUMMARY**

Scenario planning is regarded as a useful tool for strategic planning, particularly in managing uncertainty through the examination of various future scenarios. Since present decisions influence a system's future performance, foreseeing new advancements and problems is critical to the success of future plans. Rather than attempting to accurately predict the future, scenario planning assists in negotiating unexpected and complex developments. Strategic planners can use scenarios to create a more sustainable system by considering how future events can unfold, addressing uncertainties, providing insights into the long-term consequences of decisions, and identifying potential opportunities and threats.

A scenario represents a combination of potential developments, which are factors that influence systems in the future. These potential developments are characterized by specific factors and their corresponding levels, all of which have a qualitative nature. In practical scenario planning, the number of possible scenarios can reach into the millions. To formulate effective and actionable plans for the future, it is essential to focus on a manageable subset of scenarios. Therefore, the qualitative nature of the scenarios should first be quantified, and a selection process should be employed to identify a subset of scenarios for further analysis and strategic planning.

The studies presented propose a comprehensive methodology for the evaluation and selection of scenarios. Multiple criteria were utilized to assess the scenarios through factor levels from different perspectives. To quantify the factor levels, they were first evaluated with respect to multiple criteria as well as the criteria interactions. Interactions between the criteria are crucial for real-world problems, as decision-making processes often involve these interactions. The Choquet integral was employed to aggregate the evaluations considering criteria interactions, providing numerical values for the factor levels. Since the Choquet integral is defined on measures, a mathematical model was developed to revise the expert assessments thereby obtaining criteria weights that satisfy measure rules. The factor levels were then weighted using a specific criterion (i.e., consistency) to calculate scenario values. After obtaining numerical values for the scenarios, a second mathematical model was developed to select a limited number of high-quality scenarios that best represent potential futures. A total of five criteria were used in the evaluation and selection process. Additionally, a practical application has been conducted to demonstrate the real-world usage of the selected scenarios. Following the selection of scenarios, projects or objectives to be prepared for alternative futures were identified. An actor analysis was performed to determine which stakeholders should collaborate in achieving these objectives within the relevant sectors.

This approach ensures that both the evaluation and selection processes are comprehensive, incorporating realistic decision-making dynamics such as criteria

interactions and that the selected scenarios can be practically applied in strategic planning.



## İLERİ SENARYO PLANLAMA: SENARYOLARIN GELİŞTİRİLMESİ, DEĞERLENDİRİLMESİ VE SEÇİLMESİ İÇİN YENİ YAKLAŞIMLAR VE UYGULAMALARI

### ÖZET

İnsanlar her zaman içinde buldukları çevreyi daha iyi anlayabilmek ve geleceğe hazırlıklı olabilmek adına geleceğin nasıl olacağını merak etmişlerdir. Ancak doğası gereği karmaşık ve öngörülemeyen olan gelecek, ani, hızlı ve beklenmedik gelişmelerle şekillenir. Bu durum geleceği öngörmeyi zorlaştırır. Bu nedenle, belirsizliği sistematik bir şekilde ele almak, karmaşıklığı analiz etmek ve değişimlere karşı daha doğru adımlar atmak önemli hale gelmiştir. Bu gereklilikler, geleceği düşünme ihtiyacını doğurmuş ve gelecekler araştırmalarının gelişimine yol açmıştır.

Stratejik planlama gibi uzun vadeli karar alma süreçleri genellikle geleceğe dair beklentilere dayanır. Ancak, geleceğin öngörülemeyen ve bilinemez olması, bu süreçlerin sonucunda beklentilerin istenilen şekilde gerçekleşmemesine ve sürprizlerle karşılaşılmasına neden olmaktadır. Bu zorluk, gelecekler araştırmalarının en önemli kavramı olan senaryo planlamayı ortaya çıkarmıştır. Senaryo planlama, belirsizliği göz önünde bulundurarak olası gelecekleri keşfetmeyi amaçlayan bir araçtır. Olası gelişmeleri ve bu gelişmelere ilişkin reaksiyonları inceleyerek farkındalığı artırmayı hedefler. Aynı zamanda, önemli bilgilerin entegrasyonu, tutarlı ve olası alternatif geleceklerin geliştirilmesi ve senaryoların organizasyon üzerindeki etkilerinin değerlendirilmesi ile ilgilenir. Kısaca, senaryo planlamanın temel amacı, tek bir doğru gelecek yerine çeşitli sistem değişkenlerini içeren alternatif geleceklerin ortaya çıkarılmasıdır. Senaryo planlamada alternatif gelecekler senaryolar ile temsil edilir. Senaryolar, olası alternatif gelecekleri içeren çeşitli gelişmeleri kapsayarak geleceğe dinamik bir bakış açısı sunar. Çok sayıda senaryonun dikkate alınması, alternatif gelecekleri kapsamak ve belirsizliği yakalamak açısından önemlidir. Senaryo planlama endüstri, şirket veya ülke düzeyinde uygulanabilir. Stratejik planlama, firmaların hayatta kalmalarına ve rakiplerine karşı rekabet avantajı elde etmelerine yardımcı olabilirken, senaryo planlama belirsiz ve karmaşık sistemleri anlamak ve geleceği öngörmek için daha faydalı bir teknik olarak öne çıkmıştır. Organizasyonlar dış çevre ile etkileşim içinde olduklarından, bu çevreyi anlamaları ve ona uyum sağlamaları gerekir. Sonuç olarak, senaryo planlama, esneklik ve yenilik arayışında olan organizasyonlar için önemli bir araçtır.

Senaryo planlama uygulamaları, II. Dünya Savaşı dönemine kadar uzanmaktadır. RAND Corporation, Herman Kahn yönetiminde, rakiplerin olası hareketlerini öngörebilmek amacıyla savaş planlaması yapmak için senaryolar kullanmıştır. Ayrıca ABD ve Sovyetler Birliği arasında olası bir nükleer savaşla ilgili dört senaryo geliştirmişlerdir. Hudson Institute, 1960'larda iş dünyasında "düşünülemez olanı düşünme" amacıyla senaryo planlamayı uygulamaya başlamıştır. Stanford Araştırma Enstitüsü (SRI) tarafından uzun vadeli bir stratejik planlama önerilmiştir. İş dünyasını etkileyen politik, ekonomik gibi çeşitli itici güçler dikkate alınmıştır. Royal Dutch/Shell, Pierre Wack ve Ted Newland liderliğinde senaryo planlamanın

kullanımını yeni bir seviyeye taşımıştır. 1973-1974 petrol krizi patlak verdiğinde, Shell diğer petrol şirketlerinden daha fazla hazırlıklı olduğunda artan petrol fiyatlarına hızla yanıt verebilmişlerdir. Senaryo çalışmaları sayesinde, Shell dramatik gelişmelerden en az hasarla kurtulmayı başarmıştır.

Senaryo planlama etkili ama uygulaması zor bir araçtır. Çünkü senaryolar ve senaryoları oluşturan faktörler ve bu faktörlerin düzeyleri (durumları) kalitatif yapıda kavramlardır. Bu nedenle öncelikle gelecekte etkili olabilecek senaryoları belirlemek için bu kavramları ölçülebilir hale getirerek karşılaştırılabilirliğini sağlamak gerekmektedir. Literatürde senaryo planlamaya yönelik kalitatif ve kantitatif olmak üzere bir çok yöntem kullanılmaktadır. Bu çalışmalar, senaryoları ölçülebilir hale getirmek amacıyla kriter olarak genellikle tutarlılığa ya da akla yatkınlığa odaklanarak tek bir kriter üzerinden senaryo değerlendirmesi yapmaktadır. Tek bir kritere odaklanmak geleceğe dar ve tek boyutlu bir bakış açısı sunarak, çoğu zaman beklenmedik gelişmeleri göz ardı etmeye neden olmaktadır. Çünkü bu kritere göre senaryolar sayısal bir değere sahip olmakta ve bu sayısal değere göre bazı senaryolar elenmektedir. Eleme işlemi sonrasında, senaryolar arasındaki uzaklığı dikkate alan senaryo seçim algoritması kullanılarak az sayıda senaryo seçilmektedir. Bu tür bir aşamalı eleme yaklaşımı, önemli olabilecek senaryoların dikkate alınmamasına sebep olmakta, böylece bilgi kaybı ortaya çıkmaktadır.

Bu doğrultuda, kaliteli senaryo seçimi yapılabilmesi için farklı açılardan değerlendirme yapmak gerekmektedir. Aynı zamanda değerlendirmelerin uzmanlar tarafından yapılacak olması sebebiyle, değerlendirmeleri kompleks değil daha basit yapılar üzerinden yapmak sonuçların güvenilirliği açısından önemlidir. Uzman değerlendirmelerini birleştirme sürecinde, değerlendirme için kullanılan kriterlerin etkileşimlerinin de dikkate alınması daha gerçekçi ve güvenilir sonuçlar elde etme ihtimalini artıracaktır. Senaryo seçimi gibi kombinatoriyal bir problemi objektif şekilde yapabilmek için esnek bir matematiksel model geliştirmek, kısıt ve amaçları gelecek uzayını kapsayacak şekilde tanımlamak farklı ve kaliteli senaryolar elde edilmesine olanak tanıyarak geleceğe iyi bir şekilde hazırlanmayı sağlayacaktır.

Tez kapsamında yapılan iki yayında senaryo geliştirme adımına yönelik yeni metodolojiler önerilmiştir. Metodolojik katkı sunan yayınlar, senaryo değerlendirmesine ve seçimine odaklanmaktadır. Faktör düzeyleri kriterlere göre değerlendirilip, kriterlerin tekil ve birlikte etkileri dikkate alınarak faktör düzeyleri ölçülebilir hale getirilmiştir. Bu aşamadaki hesaplamalar toplamsal olmayan bir birleştirme operatörü olan Choquet integrali ile gerçekleştirilmiştir. Ardından faktör düzeylerinin değerleri tutarlılık kriteri ile ağırlıklandırılarak senaryo değerleri elde edilmiş ve senaryo seçimi için matematiksel modeller geliştirilmiştir. Üçüncü yayında ise seçilen senaryoların pratik olarak nasıl kullanılacağını gösteren bir uygulama yapılmıştır.

“A Novel Scenario Planning Approach Considering Criteria Interaction in Multi-Criteria Evaluation: An Application to Urban Mobility” isimli yayında senaryoların değerlendirilmesine ve seçimine yönelik bir metodoloji önerilmiş ve büyük bir şehrin 2035 yılındaki ulaşım seçenekleri üzerine bir uygulama yapılmıştır. Bu çalışmada kriter etkileşimlerini dikkate almak için Sugeno  $\lambda$ -ölçümü kullanılmıştır. Uzman değerlendirmelerini kolaylaştırmak için kriter ağırlıkları ve etkileşimleri dilsel olarak belirlenmiştir. Ancak sadece pozitif etkileşimin söz konusu olduğu varsayılmıştır. Senaryo seçimi için doğrusal olmayan bir model önerilmiştir. Modelde, seçilecek senaryolar arasındaki farklılık (uzaklık) maksimize edilmeye çalışılmıştır. Dört kritere

göre hesaplanan senaryo değerlerinin belli bir eşikten yüksek olması kısıt olarak kullanılmıştır.

Bir önceki yayın, sadece pozitif etkileşimin dikkate alınması gibi önemli bir varsayıma dayanmaktadır. Ayrıca model seçiminde yalnızca uzaklığın maksimize edilmesi bilgi kaybına yol açabilmektedir ve doğrusal olmayan bir model geliştirilmesi de daha karmaşık problemlerde model çözüm süresini olumsuz etkileyebilecektir. Bu yüzden “Novel Approach to Scenario Assessment and Selection” isimli yayında bu eksiklikler giderilmeye çalışılmış ve orta ölçekli bir üretim tesisinin depo sistemi için 2030 yılına ilişkin bir uygulama yapılmıştır. Çalışmada uzmanlardan kriter değerlendirmeleri önceden tanımlı ölçekte alınmıştır. Kriterlerin birlikte etkilerini belirlemek için kullanılan etkileşim kavramı da uzmanlar tarafından ikili (pozitif ya da negatif) olarak belirlenmiştir. Birleştirme operatörü olarak Choquet integrali kullanıldığından kriter ağırlıklarının ölçüm kurallarına uyması gerekmektedir. Ölçüm kurallarını sağlamak ve birden fazla karar verici olduğu durumda ortak bir değer elde etmek için ikinci dereceden bir matematiksel model geliştirilmiştir. Bu şekilde kriterlerin tekil ve birlikte ağırlıkları revize edilmiştir. Senaryo seçimi için çok amaçlı bir matematiksel model geliştirilmiş, model hem senaryoların farklılığını hem de senaryo değerlerini maksimize etmeyi amaçlamaktadır. Matematiksel modelin sonuçlarını farklı senaryoların seçimi açısından doğrulamak için Çok Boyutlu Ölçekleme Analizi (*Multidimensional Scaling*) kullanılarak, senaryolar iki boyutlu düzleme indirgenmiş ve gerekli analizler yapılmıştır. Ayrıca önerilen yaklaşımlar literatürdeki farklı yöntemlerle karşılaştırılarak önerilen yaklaşımın daha iyi sonuç verdiği ortaya konmuştur.

Bahsedilen iki yayında nihai olarak senaryo seçimi yapılmıştır. Seçilen senaryoların pratik kullanımına odaklanılmamıştır. Seçilen senaryolar geleceğe ilişkin çeşitli amaçlara veya projelere dönüştürülmektedir. Bu amaç ve projeler önceliklendirilebilir ve aktör analizi yapılarak gelecekte avantajlı durumda olmak için hangi aktörlerin iş birliği içinde olması gerektiği belirlenir. Bu doğrultuda “A Systematic Approach to the Analysis of Barriers and Drivers of the ESCO Market in Turkey” isimli yayında enerji hizmet sektörü üzerine bir çalışma yapılmış ve gerçekleştirilmesi gereken amaçlar ve aktörler incelenmiştir. Çalışmada, yapısal analiz aracılığıyla sektördeki önemli faktörler belirlenmiş ve bu faktörler doğrultusunda amaçlar geliştirilmiştir. Ardından, aktörler ve amaçlar arasındaki ilişkileri analiz etmek amacıyla MACTOR yöntemi kullanılmıştır. Bu yöntem, hem aktör-aktör hem de aktör-hedef ilişkilerini inceleyerek olası ittifakları ve çatışmaları keşfetmektedir. Sonuç olarak, müttefik aktörlerle iş birliği yaparak hedeflere ulaşmak için stratejiler belirlenmiştir.



## 1. INTRODUCTION

People have always wondered what the future will be like in order to better understand the environment they live in and to be prepared for the future. However, the future, which is inherently complex and unpredictable, is characterized by sudden and rapid changes, and also unexpected developments which makes it difficult to foresee. Therefore, it has become crucial to adopt systematic approaches to considering uncertainty, analyze complexity and take more accurate actions in response to changes. These necessities have led to thinking about the future, namely the development of futures research (Gausemeier, Fink, & Schlake, 1998).

Long-term decision-making processes such as strategic planning are often based on expectations about the future. Yet, the fact that the future is unpredictable and unknowable causes expectations not to be realized in the desired way and surprises to be encountered as a result of these processes. This challenge has given rise to scenario planning which is the most important concept in futures research domain (Bishop, Hines, & Collins, 2007). Scenario planning is a strategic tool designed to explore possible futures by accounting for uncertainty. It investigates a wide range of possible developments and responses to raise awareness (Chermack, 2011). It also deals with the integration of essential information, the development of consistent and plausible alternative futures, and the analysis of the organizational implications of scenarios. (O'Brien, 2004). In brief, the main idea of scenario planning is to evaluate alternative futures that incorporate various system variables rather than focusing on an accurate and single future (Peterson, Cumming, & Carpenter, 2003). In scenario planning, alternative futures are represented by scenarios. Scenarios offer a dynamic perspective on future by containing several developments which cover possible alternative futures (Liu et al., 2008). The concept of multiple scenarios is used to cover alternative futures and capture uncertainty. This approach can be applied at various levels, including industry, company, or country. Although strategic planning can help firms survive and obtain a competitive advantage over their competitors, scenario planning has shown to be a more beneficial approach for comprehending uncertain and complex systems and

foreseeing the future. Since organizations interact with the external environment, they must understand and adapt to it. As a result, scenario planning is an essential tool for organizations seeking to increase their flexibility and innovation (Hiltunen, 2009).

The applications of scenario planning date back to World War II, with Herman Kahn's work at the RAND Corporation using scenarios to foresee enemy actions (Schwarz, 1991; Millett, 2003; Rialland & Wold, 2009). The Hudson Institute later applied scenario planning in business, encouraging thinking about the unthinkable (Liu et al., 2008; Chermack, 2011). Notably, Royal Dutch/Shell, under Pierre Wack and Ted Newland, used scenario planning to navigate the 1973-1974 oil crisis effectively, responding swiftly to rising oil prices and minimizing damage (Schoemaker, 1991). Since then, scenario planning has been widely employed in defense, climate, production, and public services (Nguyen & Dunn, 2009).

Following the oil crisis, the majority of the companies in the U.S. started to use scenario planning (Linneman & Klein, 1983). Scenario planning facilitates the exploration of new opportunities, encourages out of the box thinking, identifies more robust strategies, enables quick responses to unexpected developments, fosters a new culture to change and improves creative thinking (Rialland & Wold, 2009). It also allows for the assessment of system vulnerabilities and potential adaptation strategies. However, research on scenario planning studies can be expensive and challenging due to the need to assemble a team of experts and organize meetings and workshops to gather their opinions regarding the problem area (Millett, 2003).

Scenario planning studies are classified into three groups (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006).

1. "Predictive Scenarios" answer the question "What will happen?" and try to forecast what is going to happen. The scenarios are based on historical data and related to likelihood of the future developments. Trend plays an important role in forecasting futures. Yet, unexpected developments can be difficult to consider.
2. "Explorative Scenarios" deal with the question "What can happen?" and consider possible developments, driving forces to explore a wide range of future from different perspectives. These scenarios encourage the team of experts to explore unexpected developments.

3. “Normative Scenarios” seek to answer the question “How can a specific target be reached?”. The scenarios are based on specific starting and ending points. The ways to achieve desirable targets are tried to be found.

The studies in this thesis focus on the use of exploratory scenarios to examine a wide range of possible future developments.

The explorative scenario planning approach typically consists of five phases which are scenario preparation, scenario field analysis, scenario prognostic, scenario development and scenario transfer (Gausemeier et al., 1998).

Phase 1 (Scenario Preparation): In this phase, a scenario field which may be an enterprise or a technology is defined, and the current situation is assessed typically through strengths and weaknesses.

Phase 2 (Scenario Field Analysis): Scenario field is described over a large number of influence factors, constituted by external and internal factors. However, key factors which play an essential role in scenario development should be determined to proceed further phases with a manageable number of relevant factors.

Phase 3 (Scenario Prognostic): In this phase, factor levels are identified. These levels cover possible developments in the future regarding each key factor.

Phase 4 (Scenario Development): Scenarios, representing possible futures, are the combination of factor levels and are assessed with respect to a criterion, typically consistency. The number of scenarios should be limited to maintain cognitive manageability. Several methods such as clustering are used to eliminate scenarios and reduce complexity.

Phase 5 (Scenario Transfer): In this phase, the effects of final scenarios that are treated as inputs of the strategic management process are analyzed. Opportunities and threats that concern the scenario field are determined. Accordingly, the related projects or strategies are developed. At this point, actor analysis methods can be employed to reveal potential alliances and conflicts among actors to develop future collaborations. Therefore, corporate strategies can be identified as either responsive or proactive, depending on how they address the opportunities and threats.

Scenario development is one of the most challenging phases due to the qualitative nature of its elements, including factors, factor levels and scenarios. Factors represent

driving forces that affect the study area, which may include economic, political, and technological factors like inflation, usage of Artificial Intelligence (AI) or regulations. Factor levels represent different situations of these factors. For instance, inflation can be categorized as high, moderate, low, or deflationary. Similarly, governments can highly promote the usage of AI and provide incentives, be neutral, or impose strict regulations that hinder AI development. Each combination of factor levels forms the basis for distinct scenarios.

Assessing scenarios is a vital part of the scenario development phase. This assessment is based on several criteria, some of which are listed in Table 1.1. Not every criterion is suitable for every class of scenario planning studies, so careful consideration of both the method and scenario type is essential when selecting criteria. In our works, we make use of these criteria, while also identifying new criteria that align with our proposed methodology. Selecting a small number of high-quality scenarios is another significant part that follows the assessment process in scenario planning. Thus, it is essential to develop a robust methodology for selecting criteria, evaluating, and ultimately choosing the most relevant scenarios.

**Table 1.1 : Quality criteria in Scenario Development**

Scenario Quality Criteria	Explanation	Measurement
Consistency	Scenarios should not contain conflicting factor levels (Wilson, 1998).	-2 ( inconsistent) - 2 ( induce each other) (Tietje, 2005). It is based on the assessment of factor level pairs.
Plausibility	Scenarios should be realizable (Wilson, 1998).	0 (Definitely implausible) – 3 (Definitely Plausible) (Coyle & Yong, 1996). It is based on the assessment of factor level pairs.
Different (i.e. diversity, distance)	Scenarios should be structurally different from each other (Tietje, 2005).	Scenarios are compared with each other based on factor levels (Tietje, 2005).
Comprehensibility	Scenarios should be detailed enough (Wilson, 1998).	Workshops
Probability	Scenarios should be probable (Bradfield, Wright, Burt, Cairns, & Van Der Heijden, 2005).	Decision makers assign probabilities to scenarios or factor levels.

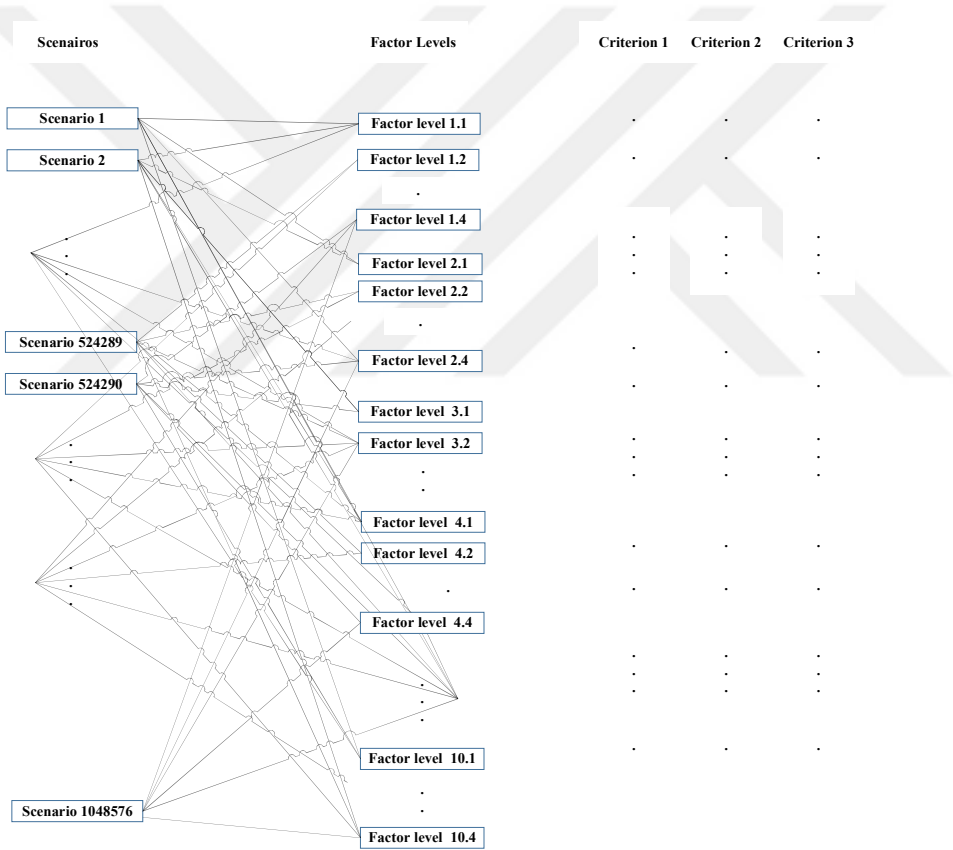
**Table 1.1 (continued):** Quality criteria in scenario development

Scenario Quality Criteria	Explanation	Measurement
Relevance	Scenarios should be appropriate to the decision field (Durance & Godet, 2010).	Workshops
Creativity	Scenarios should provide novel solutions (Pereverza, Pasichnyi, Lazarevic, & Kordas, 2017).	Workshops
Coverage	Scenarios should cover relevant developments, strategic options, external and internal factors (Tourki, Keisler, & Linkov, 2013).	The number of scenarios among final scenarios that are aligned with the goal / Total number of scenarios that are aligned with the goal
Desirable	Scenarios should be aligned with the desired visions (Pereverza et al., 2017).	Workshops
Efficient	Scenarios should be highly representative and consistent (Tietje, 2005).	Workshops
Tangible	Scenarios should be comprehensive and explicit (Wiek & Binder, 2005).	Workshops
Shared	Decision makers should agree on the scenarios (Wiek & Iwaniec, 2014).	Workshops
Manageable number of scenarios	The number of final scenarios should be small to decrease complexity and redundancy for strategic planning (Tietje, 2005).	There is no defined rule, but researchers set a specific number for final scenarios usually between 3-7.

## 1.1 Scope and Purpose of the Thesis

This thesis focuses on the fourth and fifth phases of the scenario planning process: scenario development and scenario transfer. Scenario development aims to construct scenarios, evaluate them and obtain a manageable number of scenarios among the whole scenario set after determining the scenario field, its factors and corresponding factor levels, while scenario transfer aims to convert the selected scenarios into strategies.

Scenarios are constructed by combining one factor level from each factor. For instance, consider a problem consisting of 10 factors each with four levels, the total number of scenarios will be  $4^{10}$  which equals 1,048,576. In real life problems, the number of factors and levels can be significantly higher, leading to a larger number of scenarios. It is not practical to assess such a large number of scenarios as it is difficult for experts to comprehensively assess these complex scenarios. Moreover, as the scenarios are constructed by a number of factor levels, it would not be reliable to make an assessment considering all factor levels at the same time. Therefore, it would be more reasonable to ensure that the factor levels become measurable, and then obtain scenario values through the evaluations on a limited number of factor levels. The structure of this approach is given in Figure 1.1.



**Figure 1.1 :** The structure of the problem.

The one of the main objective of the thesis is to select a manageable number of scenarios that cover as much of the future space as possible. However, for effective scenario selection, scenarios need to be both measurable and comparable. Since scenarios and their associated factor levels are inherently qualitative, they are not directly measurable or comparable. To address this, the factor levels will first be

quantified using relevant criteria. Each factor level will be evaluated based on multiple criteria, and these evaluations will be weighted and combined to produce numerical values for the factor levels. Subsequently, scenarios will be quantified by aggregating the numerical values of the factor levels that construct each scenario. A small number of scenarios will then be selected using appropriate techniques.

Another main objective of the thesis is to demonstrate how the selected scenarios can be converted into actionable strategies, as scenario transfer is just as important as scenario selection. Since scenarios outline potential future directions, it is pivotal to use them to identify which objectives will be important and which actors will need to collaborate. This approach allows for the identification of strategies aligned with these objectives. Ultimately, this process ensures that the insights gained from scenario planning are effectively applied to guide decision-making and strategic planning.

The objectives of the study and how to address them are provided as follows:

- **Identifying criteria:** Criteria which are capable of evaluating factor levels and also significant for the study area are identified.
- **Establishing relevant scales:** Appropriate scales for evaluating factor levels and determining criteria weights are established.
- **Aggregating criteria evaluations considering criteria interaction:** Evaluations of factor levels with respect to criteria are aggregated taking into account criteria interactions. Consideration of criteria interactions is critical for producing more realistic and reliable results. In real life decision making problems, the criteria may interact, resulting in amplified or diminished effects. For example, when two highly valued criteria are satisfied, other criteria may lose importance. To achieve this, it is necessary to use non-additive operators for the integration process.
- **Developing a model to revise evaluations:** Non-additive operators are based on measure theory, thus evaluations must satisfy the measure rules. So, evaluations are revised complying with these rules.
- **Constructing an indicator to calculate scenario values:** An indicator combining the factor level values to calculate scenario values is proposed to ensure that the scenarios are comparable.

- **Formulating a mathematical model for scenario selection:** A mathematical model is developed to help objectively select a small number of scenarios.
- **Scenario transfer:** Converting the selected scenarios into strategies is crucial for the practical application of scenario planning. Since scenarios highlight potential future developments, it becomes essential to identify objectives based on the selected scenarios. Following this, actor analysis is conducted to explore potential alliances and conflicts over the objectives. Strategies are then developed in collaboration with allied actors to achieve these goals. In this regard, it is proposed to use the MACTOR method, as it can be easily integrated with the proposed scenario selection approaches.

## 1.2 Contributions

Existing studies in the literature use a single criterion for scenario assessment, usually focused on consistency to make scenarios measurable. However, this approach provides a narrow, one-dimensional vision of the future, frequently ignoring potential unexpected developments. Typically, a scenario elimination procedure is conducted based on this criterion, followed by a distance-based selection algorithm to represent diverse scenarios. Such an iterative approach and relying on a single criterion lead to a loss of valuable information. Evaluating the future from multiple perspectives and making decisions based on different considerations will lead to better results.

The proposed methodology introduces a novel approach by employing a total of five criteria. Three of these criteria, which are plausibility, adaptability and significance (or sustainability) are utilized to evaluate factor levels, and the aggregation process incorporates interactions between these criteria. The factor levels are weighted according to the consistency criterion to obtain scenario values. This approach presents a comprehensive methodology for combining criteria evaluations, offering more reliable results by accounting for interactions among criteria. The final criterion, distance, is used in the scenario selection phase where two mathematical models are developed to select a manageable number of scenarios, considering several constraints. The first model maximizes only distance among scenarios, while the second is a multi-objective model that integrates both distance and scenario values. The latter model presented provides flexibility to practitioners, allowing for adjustments based on the importance of different parameters in the objective function.

To the best of our knowledge, this is the first time where multiple criteria are simultaneously utilized, also with their interactions employed by Choquet integral as a non-additive aggregation operator. The multi-objective scenario selection model provides a comprehensive framework considering multiple criteria and diverse scenarios to ensure a more accurate and representative selection. The methodology effectively reduces information loss and enhances the comprehensiveness and accuracy of the scenario assessment and selection process.

Studies on scenario evaluation and selection in the literature often lack a practical perspective on how to use the selected scenarios. However, the selected scenarios offer valuable insights into what the future environment may look like. Developing objectives, projects, or opportunities aligned with these scenarios is key to making the insights actionable. Therefore, after selecting the scenarios, determining objectives based on them, conducting actor analysis using the MACTOR method, and identifying strategies informed by this analysis provide a practical framework for utilizing the scenarios effectively.

### **1.3 Publications and Their Relations**

Within the scope of the thesis, three international publications about scenario planning have been produced apart from conference papers. Two of them propose new methodologies for the scenario development phase, while the third demonstrates the practical application of the selected scenarios proposing a framework for utilizing scenario outputs such as objectives and projects. Methodological papers focus on scenario evaluation and selection. In these studies, factor levels were evaluated with respect to multiple criteria, and Choquet integral was employed as a non-additive aggregation operator to aggregate evaluations, taking into account the criteria interactions. The evaluations were combined to obtain the numerical values of the factor levels. Factor levels were weighted with the consistency criterion to obtain scenario values and mathematical models were developed for scenario selection.

In the publication titled “A Novel Scenario Planning Approach Considering Criteria Interaction in Multi-Criteria Evaluation: An Application to Urban Mobility” a methodology for scenario evaluation and selection is proposed, with an application focused on urban transportation in a metropolitan city for the year 2035. In this study, the Sugeno  $\lambda$ -measure was used to account for criteria interactions. To simplify the

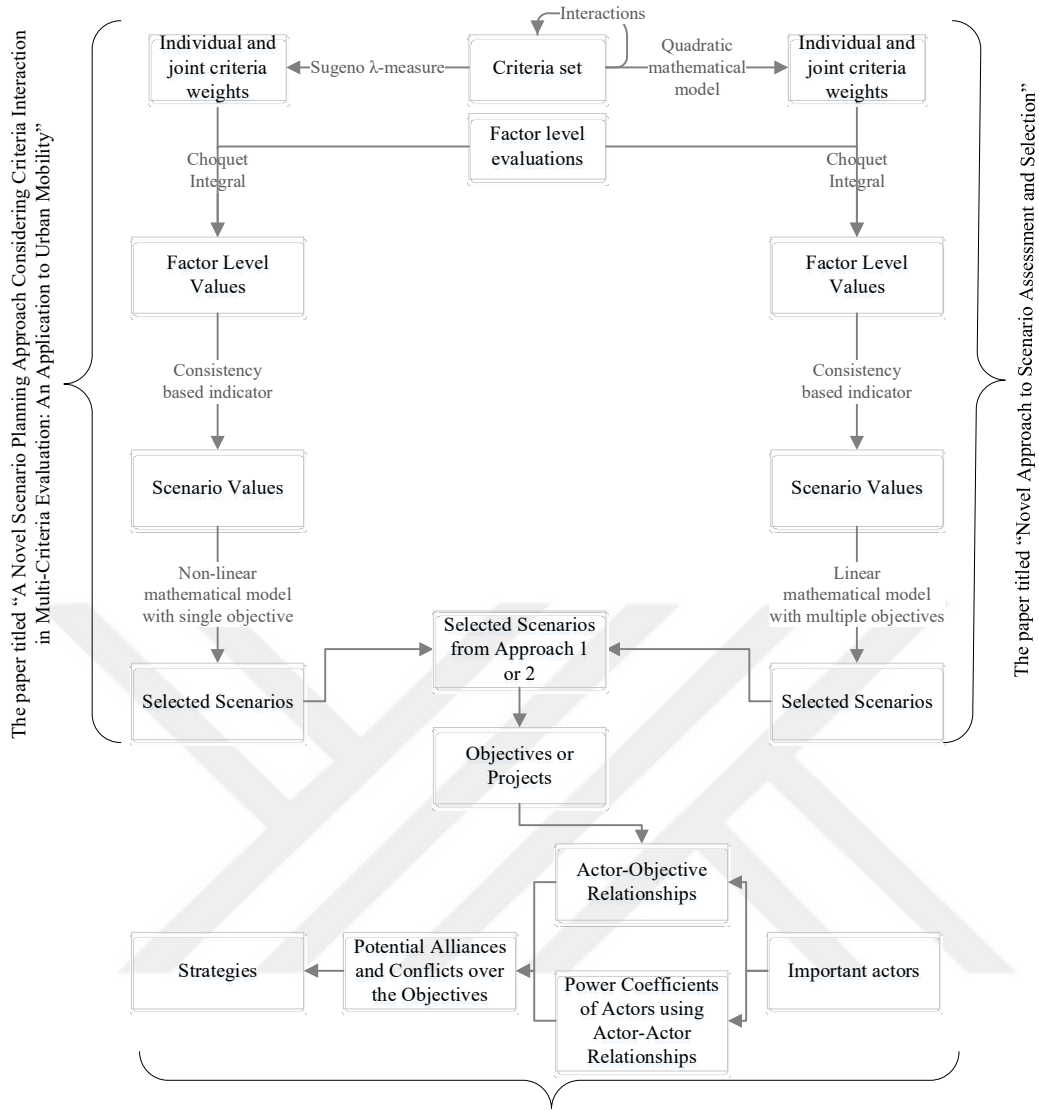
experts' evaluations, criteria weights and interactions were captured linguistically. However, only positive synergies are assumed to exist. A non-linear mathematical model was developed for scenario selection, aiming to maximize the differences (in terms of distances) between the selected scenarios. Additionally, the values derived from four criteria, based on the factor levels of the scenarios, were constrained to be higher than a certain threshold to ensure that the scenarios attributed higher values by the experts are considered.

In the first study mentioned, assuming the existence of only positive synergy constitutes a significant drawback. Additionally, the mathematical model focused solely on maximizing distance during scenario selection, resulted in some information loss, and non-linearity could negatively affect the solution time in complex problems. To address these shortcomings, the study titled “A Novel Approach to Scenario Assessment and Selection” was prepared, featuring an application for the warehouse system of a medium-sized manufacturing facility, projecting to the year 2030. In the study, experts provided evaluations of factor levels and both individual and joint criteria weights using a pre-defined scale. Additionally, the synergies between criteria were assessed as binary, being either positive or negative. Since the Choquet integral was used as the aggregation operator, it was essential for the criteria weights to comply with the measurement rules. To ensure compliance with these rules and to derive a consensus value when multiple decision-makers were involved, a quadratic mathematical model was developed. In this way, the individual and joint weights (with interactions) of the criteria were revised. A multi-objective mathematical model for scenario selection, proposing a flexible model that aims to maximize both scenario values and the differences between scenarios, was developed. The model results in terms of the selection of diverse scenarios were validated using Multidimensional Scaling (MDS) by projecting the scenarios onto a two-dimensional plane. Additionally, the proposed method was compared with several methods used in the literature to evaluate its effectiveness.

In the two publications mentioned, the focus was the selection of a manageable number of scenarios. However, the practical application of these selected scenarios was not explored. Considering the selected scenarios, various future objectives or projects can be developed. To ensure a strategic advantage, it is essential to analyze these objectives and conduct an actor analysis to determine with whom collaboration should be

pursued. Therefore, in the study titled “A Systematic Approach to the Analysis of Barriers and Drivers of the ESCO Market in Turkey,” an application was conducted on the energy service contracting market, examining the necessary objectives and relevant actors. The study identified key barriers through structural analysis, and objectives were developed to overcome these barriers. The MACTOR method was then used to analyze the relationships between actors and objectives. The method explores potential alliances and conflicts by examining both actor-actor and actor-objective relationships. As a result, strategies for achieving the objectives in collaboration with allied actors were determined. This approach provides a systematic framework for transitioning from scenario selection to strategy development, by analyzing the objectives corresponding to the selected scenarios and the relevant actors.

The relations among publications are given in Figure 1.2. and the overview of the research papers is given in Table 1.2.



The paper titled "A Systematic Approach to the Analysis of Barriers and Drivers of the ESCO Market in Turkey"

**Figure 1.2 : Relations among publications**

**Table 1.2 : Overview of research papers**

Papers	Type of Contribution	Main Concepts	Proposed and used methods	Application Areas
Paper 1 (Chapter 2)	Methodological	Criteria, factors and constraints	Non-additive measure and integral, criteria based weighting indicator, Non-linear mathematical model	Urban Mobility in a Metropolitan city
Paper 2 (Chapter 3)	Methodological	Criteria, factors and constraints	Quadratic and Linear mathematical models, Non-additive integral, criteria based weighting indicator	Warehouse of a Production Facility
Paper 3 (Chapter 4)	Applied	Actors and Objectives	Structural Analysis and MACTOR	Energy Service Contracting Market



## **2. A NOVEL SCENARIO PLANNING APPROACH CONSIDERING CRITERIA INTERACTION IN MULTI-CRITERIA EVALUATION: AN APPLICATION TO URBAN MOBILITY<sup>1</sup>**

Scenario planning has been recognized as a valuable approach for strategic planning to address uncertainty by exploring possible future scenarios (Stead & Banister, 2003; Stojanović, Mitković, & Mitković, 2014). Since decisions made today will affect the future performance of a system, foreseeing future developments and challenges is a prerequisite for success in future plans. Rather than accurately predicting the future, scenario planning studies support dealing with unexpected and challenging future developments (Enoch et al., 2020). Scenarios can help strategic planners build a sustainable system by exploring how future events may evolve through addressing uncertainties, providing insight into long-term impact of decisions and, revealing opportunities and threats.

A scenario represents a combination of potential developments in the future (Bood & Postma, 1997). Scenarios can be constructed by qualitative approaches such as deductive method (Ramírez & Selin, 2014) or by using combinations of future projections (Schoemaker, 1995). However, qualitative research often focuses on exploring complex phenomena in-depth, but it may provide a limited breadth of information (Behling, Gifford, & Tolliver, 1980). To reduce complexity and difficulty in the evaluation phase of scenarios, building scenarios based on combinations of future developments is more appropriate due to their decomposable structure (Gausemeier et al., 1998).

To be able to evaluate and compare scenarios, various criteria have been suggested. The common criteria in the literature to evaluate scenarios are plausibility, consistency, probability, novelty, relevance, completeness, transparency, and diversity (Amer, Daim, & Jetter, 2013). Despite the variety of quality criteria, many quantitative

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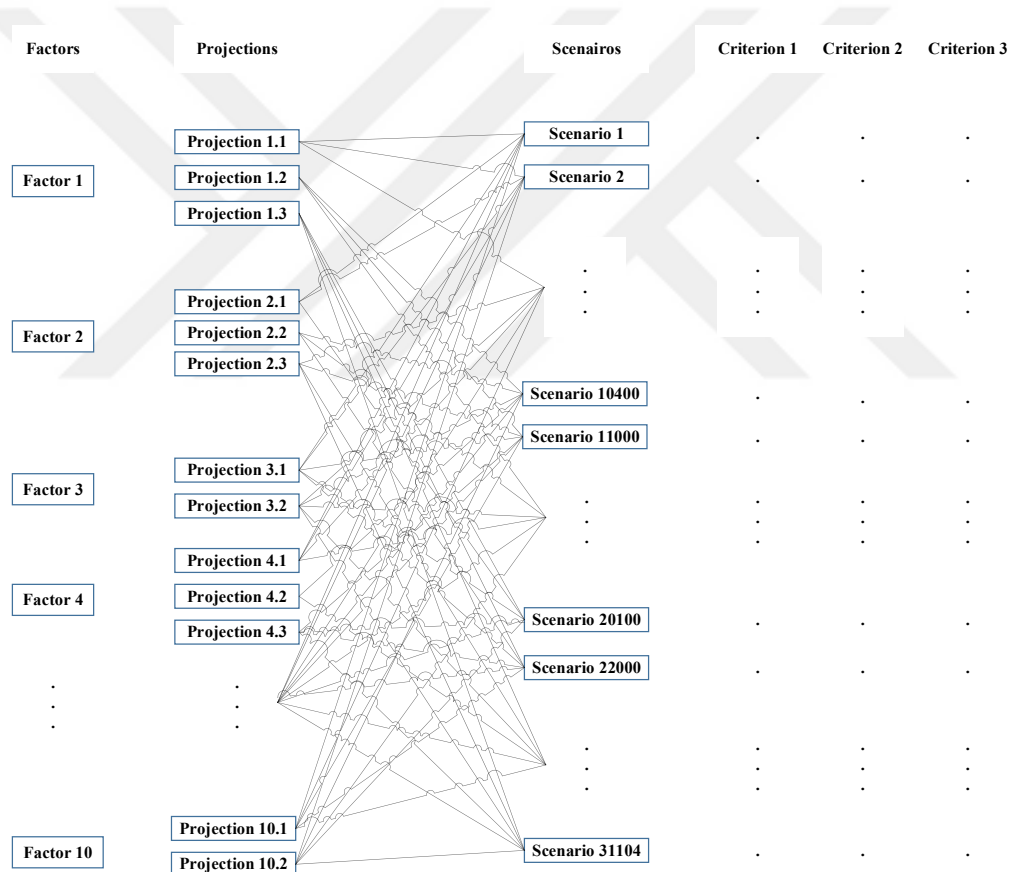
<sup>1</sup> This chapter is based on the paper “Yanmaz, O., & Asan, U. (2024). A novel scenario planning approach considering criteria interaction in multi-criteria evaluation: An application to urban mobility. *Decision Science Letters*, 13(2), 461-470.”

methods in which scenarios can be decomposed into simpler future states (e.g. projections) commonly use plausibility, consistency and diversity (i.e. distance) (Gausemeier et al., 1998; Tietje, 2005; Lord, Helfgott, & Vervoort, 2016). Based on the values obtained through these criteria, an elimination procedure is implemented to derive a manageable number of scenarios. This is often necessary, since in a scenario study, there can be thousands or even millions of scenarios depending on the number of factors and their alternative future states. Therefore, the number of scenarios should be reduced before initiating the strategic planning process to reduce complexity. However, most of the methods perform elimination procedures that consider the criteria only sequentially to evaluate scenarios. This leads to the loss of valuable information about possible futures. Using sequential elimination or relying only on a single criterion might result in ignoring some significant scenarios that might occur in the future.

Scenario planning begins with identifying significant factors relevant to the area of concern and their projections which are different future developments of factors. Each scenario is constructed by combining one projection from each factor. All the combinations create the scenario set. Scenarios can be thought of as alternatives in a typical multi criteria decision making (MCDM) problem. The scenarios need to be evaluated with respect to criteria. In this respect, it is similar to MCDM problems. However, since there are too many scenarios in a scenario planning practice, depending on the number of factors and their projections, and scenarios are based on various projections, it is really hard and complex to evaluate scenarios directly. So it will be more appropriate to evaluate projections and then aggregate their values. This approach offers an advantage for the simplification of the evaluation process. The framework of the problem is given in Figure 2.1.

To address the limitations in the literature (the most relevant papers are given in Table 2.1 for comparison purposes), a novel approach is proposed to improve scenario evaluation and selection process in this study. The main contribution of the scenario evaluation process lies in obtaining scenario values by considering multiple criteria and their interactions. Criteria that may appear insignificant on their own can have a substantial impact on the system when considered jointly, therefore, interactions play a crucial role in determining the outcomes of various systems (Cigdem Kadaifci, Asan, & Bozdag, 2020). By considering the weights of individual as well as joint criteria, the

values of future projections are expected to be more accurate and representative due to reduced information loss. To calculate joint weights of criteria, a Sugeno  $\lambda$ -measure based approach is presented. Choquet integral is used to aggregate multiple criteria assessments considering their interactions. Following the scenario evaluation process, scenario selection is performed by means of a mathematical programming model to select a set of scenarios which cover a wide range of future developments. This minimizes the risk of overlooking diverse possible future developments. The proposed approach is applied to an urban mobility system in a metropolitan area, where uncertainties are high due to many uncontrollable factors. Exploring scenarios for long-term planning in metropolitan areas is crucial for gaining insights into future transportation needs, modes and technologies.



**Figure 2.1 : Scenario building and evaluation structure**

**Table 2.1 : Related Studies in the Literature**

Source	Quality Criterion / Criteria	Multiple Criteria Consideration	Criteria Interaction	Criteria for Scenario Elimination	Scenario Selection Method and Criteria
(De Kluiver & Moskowitz, 1984)	Probability	X	X	Probability	Optimization based on probability
(Gausemeier et al., 1998)	Consistency	X	X	Consistency	Cluster analysis based on similarity
(Tietje, 2005)	Consistency and distance	✓ (Sequentially)	X	Consistency	Optimization based on distance
(Bruno Mazzorana, Hübl, & Fuchs, 2009)	Consistency and distance	✓ (Sequentially)	X	Consistency	Optimization based on distance
(Lord et al., 2016)	Plausibility and diversity	✓ (Sequentially)	X	Plausibility	Optimization based on diversity
(Seeve & Vilkkumaa, 2022)	Consistency and diversity	✓ (Sequentially)	X	Consistency	Optimization based on diversity
Proposed Approach	Plausibility, Sustainability, Adaptability, Consistency, Dissimilarity	✓ (Simultaneously)	✓	Plausibility, Sustainability, Adaptability, Consistency	Optimization based on dissimilarity

The rest of the paper is organized as follows. The theoretical basis of fuzzy measure and the Choquet integral, and the methodology of the proposed approach are described in Sections 2 and 3, respectively. An application about the evaluation and selection of urban mobility scenarios is presented in Section 4. Finally, conclusions and limitations of the study are provided in Section 5.

## 2.1 Theoretical Basis Of The Proposed Approach

### 2.1.1 Sugeno $\lambda$ -measure

The suggested method incorporates a fuzzy (i.e. non-additive) measure to evaluate scenarios based on multiple criteria. Therefore, it would be useful to briefly describe a fuzzy measure.

A fuzzy measure does not follow the usual rules of addition. That means, the total measurement may not simply be the sum of the individual measurements, as interactions or relationships between the parts play a significant role in determining the overall measurement. By considering the interactions between parts, fuzzy measures provide a more comprehensive understanding of the properties being measured. There are different types of fuzzy measures.  $\lambda$ -measure, as one of the well-known fuzzy measures (Mohamed & Xiao, 2003), was proposed by Sugeno (1977) to decrease the complexity of the decision making process.  $\lambda$ -measure allows us to calculate the measure of any set of elements taking into account interactions among them with the unique parameter  $\lambda$  if the measures of any two partitions of the set are known. In this way, the  $\lambda$ -measure captures the complex dependencies and interactions between different subsets of elements in the set. However,  $\lambda$  value is unique for all subsets. Fuzzy measure and  $\lambda$ -measure are defined as follows in Definitions 1 and 2, respectively:

Definition 1: (Michio Sugeno, 1974) Let  $X$  be a finite set and a fuzzy measure  $\mu$  defined on  $X$  be a set function  $\mu: P(X) \rightarrow [0,1]$ , where  $P(X)$  is power set of  $X$ . It has following properties:

- i. Boundary,  $\mu(\emptyset) = 0, \mu(X) = 1$ .
- ii. Monotonicity,  $\mu(A) \leq \mu(C)$  if  $A \subseteq C$ .

Definition 2: Let  $X = \{x_1, x_2, x_3, \dots, x_n\}$  be a finite set and consider  $\lambda \in (-1, \infty)$ ,  $\lambda$ -measure is a function  $g_\lambda : 2^X \rightarrow [0, 1]$  such that it satisfies the following conditions:

- i.  $g_\lambda(X) = 1$
- ii. If  $A, B \in 2^X$  then  $g_\lambda(A \cup B) = g_\lambda(A) + g_\lambda(B) + \lambda g_\lambda(A)g_\lambda(B)$  with  $A \cap B = \emptyset$

Using these properties, Eq. 2.1 is obtained to find the unique value of  $\lambda$  on the interval (Leszczyński, Penczek, & Grochulski, 1985).

$$\lambda + 1 = \prod_{i=1}^n (1 + \lambda g_i), \text{ where } g_i = g_\lambda(x_i) \quad (2.1)$$

### 2.1.2 Choquet integral

Choquet integral (Choquet, 1954) is a non-additive aggregation operator that relies on fuzzy measures (Ridaoui & Grabisch, 2016). It combines multiple criteria values into a single value representing individual weights of criteria and also interactions among them. In many application areas especially decision making, there exist interactions among criteria or elements (Shieh, Wu, & Liu, 2009). Choquet integral (*ChI*) is a more appropriate aggregation function for such problems than classical operators such as weighted sum and ordered weighted averaging to produce more accurate results. The basic definitions are given as follows:

Definition 3: (Grabisch, 1995) Let  $\mu$  be a fuzzy measure on the set  $X = \{x_1, x_2, x_3, \dots, x_n\}$ . The ChI of a function  $f: X \rightarrow [0, \infty]$  w.r.t. fuzzy measure  $\mu$  is defined as:

$$\int f dg = \sum_{i=1}^n (f(x_i) - f(x_{i-1}))\mu(A_i) \quad (2.2)$$

where the indices  $i = 1, 2, 3, \dots, n$  represents the position of permuted function  $0 \leq f(x_1) \leq f(x_2) \leq f(x_3) \leq \dots \leq f(x_n)$ ,  $f(x_0) = 0$  and  $A_i \subseteq X$ .

## 2.2 Proposed Approach

In this study, a novel approach is proposed to evaluate and select scenarios to be used in the strategic planning process. As explained in Section 1, scenarios are representations of possible developments that arise from a variety of factors. Possible developments of each factor are described by future projections and a scenario is constructed by combining one projection from each factor. Since scenarios could not be evaluated efficiently as a whole due to their complex structures, they are evaluated based on these projections. This is essential for simplifying the evaluation process. Projections are assessed with respect to multiple criteria and the assessments are aggregated using *ChI* which considers joint criteria weights that represent interactions between criteria. A new Sugeno  $\lambda$ -measure based approach is suggested for the calculation of joint criteria weights. Then, the overall value of each scenario is

calculated using aggregated projection pairs weighted by their consistency. Since the number of scenarios might be excessive based on the number of factors and projections, it is crucial to select a representative set of scenarios that effectively covers the future and ensures a manageable number of scenarios. Accordingly, a mathematical programming model is developed to address this combinatorial problem. In summary, the proposed approach provides a systematic framework for scenario evaluation and selection that can help decision makers taking part in strategic planning. The steps of the approach are given below:

**Step 1. Identifying factors, their projections and criteria:** First, factors and their possible future projections relevant to the problem area are identified, then, related quality criteria are determined based on expert opinions and literature review. The factors are denoted by the set  $F = \{ft_1, \dots, ft_I\}$  and the set of projections of factor  $i$  are  $ft_i = \{p_{i1}, \dots, p_{iJ}\}$ , where  $ft_i \in F$ , factor indices  $i = 1, \dots, I$  and level indices  $j = 1, \dots, J$ . The criteria are represented by the set  $C = \{c_1, \dots, c_U\}$ , where  $c_u \in C$  and indices  $u = 1, \dots, U$ .

**Step 2. Assessment of projections and criteria weights:** Projections are assessed with respect to the determined criteria and experts assign individual weights to each criterion based on a predefined scale. The value of the projection  $p_{ij}$  w.r.t criterion  $c_u$  and the weight of the criterion  $c_u$  represented by fuzzy measures are denoted by  $f_{p_{ij}}(c_u)$  and  $\mu(c_u)$  (i. e.  $\mu_{c_u}$ ).

**Step 3. Calculation of joint criteria weights:** The Sugeno  $\lambda$ -measure is a widely used method to calculate joint criteria weights. However, it may be restrictive due to using a single parameter value for all interactions. Each criteria subset has its own unique relationship, so it needs to have a specific  $\lambda$  value. To address this issue, a new method is proposed to calculate joint criteria weights considering different  $\lambda$  values for each criteria subset. Experts provide assessments using rating scale corresponding to criteria interactions in the interval  $[0,1]$ . Using Eq. 2.3, joint criteria weights are calculated by satisfying the fuzzy measure properties.

$$\mu_E = \max(\mu_A + \mu_B + \lambda_E \mu_A \mu_B) \quad (2.3)$$

where  $\forall E \subseteq X, \forall A, B \subset E, |A| \leq |B| < |E|, A \cap B = \emptyset$  (i. e.  $\mu_{123} = \max(\mu_1 + \mu_{23} + \lambda_{123} \mu_1 \mu_{23}, \mu_2 + \mu_{13} + \lambda_{123} \mu_2 \mu_{13}, \mu_3 + \mu_{12} + \lambda_{123} \mu_3 \mu_{12})$ ). The *max*

function is performed to satisfy the monotonicity property. If  $\mu_X \neq 1$ , the weights are normalized using the equation  $\mu_A^* = \frac{\mu_A}{\mu_X}$ .

**Step 4. Calculation of projection values:** The ChI is used to obtain overall value for each projection denoted by  $V_{p_{ij}}$  by aggregating assessments with respect to multiple criteria using Eq. 2.4.

$$V_{p_{ij}} = \sum_{u=1}^U \left( f_{p_{ij}}(x_u) - f_{p_{ij}}(x_{u-1}) \right) \mu_{A_u}^* \quad (2.4)$$

**Step 5. Calculation of scenario values:** Since scenarios are constructed by combining projections of different factors, scenario values are calculated by aggregating projection values obtained in the previous step. In aggregating the projection values, consistency, which serves as the most commonly employed criterion in scenario planning (Amer et al., 2013), is utilized as the weighting factor. The main assumption is that the consistency between projections determines the consistency of the scenario. In this study, only pair-wise consistency is considered to minimize the complexity that arises from including higher-level combinations (i.e. bundles of three or more projections). The proposed equation to obtain scenario values is given in Eq. 2.5.

$$SV_k = \sum_{\{p_{ij}, p_{yz}\} \in W} (V_{p_{ij}} + V_{p_{yz}}) \text{con}_{p_{ij}p_{yz}} \quad (2.5)$$

where  $\text{con}_{p_{ij}p_{yz}}$  is the consistency value for the projections  $p_{ij}$  and  $p_{yz}$  in scenario  $k$ ,  $S_k = [p_{1j} \dots p_{Ij}]$ ,  $SV_k$  is the value of scenario  $k$ ,  $k = 1, \dots, K$ .  $W$  is the set of two-element subsets of the scenario  $k$ .

**Step 6. Selection of a manageable number of scenarios:** A small and manageable number of scenarios should be selected to simplify and improve the strategic planning process. Also, strategic planning should be based on effective and diverse scenarios to cover future developments. Thus, organizations can adequately prepare for the future and ensure their readiness to tackle upcoming challenges. A nonlinear programming model is developed to select a reasonable number of scenarios under several constraints. The aim is to maximize the total distance between the selected scenarios. A dissimilarity measure is defined to determine the distance between scenarios as given in Eq. 2.6 (Prasetyo & Purwarianti, 2014).

$$D_{kt} = \frac{|F|-m}{|F|} \quad (2.6)$$

where  $D_{kt}$  is the dissimilarity (i.e. distance) value between scenario  $k$  and scenario  $t$ ,  $|F|$  is the number of factors and  $m$  is the number of projections matching in scenario  $k$  and scenario  $t$ .

The model is formulated as follows:

Indices

$k, t$ : Index for scenarios  $(1, \dots, K)$

Parameters

$SV_k$ : The value of scenario  $k$

$D_{kt}$ : The distance between scenario  $k$  and  $t$

$TH$ : Threshold value for scenario values

$MaxS$ : The maximum number of scenarios to be selected

$MinD$ : The minimum distance between scenarios to be selected

$M$ : Big number

Decision Variables

$S_k$ :  $\begin{cases} 1, & \text{if scenario } k \text{ is selected} \\ 0 & \text{o/w} \end{cases}$

$$Max \sum_k^{K-1} \sum_{t,t>k}^K D_{kt} S_k S_t \quad (2.7)$$

$$\sum_{k=1}^K S_k \leq MaxS \quad (2.8)$$

$$S_k = 1 \quad k = argmax_{i=1,\dots,K} SV_i \quad (2.9)$$

$$TH - SV_k \leq M (1 - S_k) \quad \forall k \quad (2.10)$$

$$D_{kt} \geq MinD S_k S_t \quad \forall k, t \text{ ve } k < t \quad (2.11)$$

$$S_k \in \{0,1\} \quad \forall k \quad (2.12)$$

The objective function (Eq. 2.7) aims to select a scenario set which has the maximum total distance between scenarios. The number of scenarios to be selected is limited by Eq. 2.8. Eq. 2.9 ensures that the scenario with the largest value is selected. Eq. 2.10 guarantees that scenarios are eliminated if their values are lower than the threshold value. Eq. 2.11 ensures that there is at least a specified distance between scenarios to be selected.

The model produces a scenario set which includes diverse scenarios being able to cover a wide range of possible future developments with relatively high scenario values based on several criteria.

### **2.3 Scenario Planning Application for Future Transport**

Urban mobility needs are changing due to environmental, social, technological and economic factors. Climate change, technological advancements in electric and autonomous vehicles, shared mobility, and scarcity of energy resources necessitate a shift from conventional transportation that has not provided economical and sustainable solutions. In order to address these issues and satisfy residents' expectations, effective strategies must be developed. Especially, metropolitan cities face even more challenging problems including growing population, traffic congestion, air quality, parking, safety, noise pollution, accessibility and integration of transport modes. Moreover, the dynamic nature of these cities increases uncertainty, making it difficult to develop strategies. Therefore, a scenario planning study was performed to explore potential scenarios for 2035 that help to build a sustainable future transport plan for a metropolitan city and also show the applicability of the proposed approach.

According to experts' opinions and literature review, 12 factors and 29 projections in total that are expected to be highly effective in future transport were identified. The expert group consists of a team of 11 individuals comprising transportation analysts, academics, and public transport planners. The required information was obtained through interviews.

Factor and projections are given in Table 2.2. Three criteria were defined to assess projections, which are plausibility ( $c_1$ ), sustainability ( $c_2$ ), and adaptability ( $c_3$ ). Plausibility measures the degree of being capable of happening. Sustainability quantifies (either in positive or negative way) the level of environmental and economic contribution to sustainability of the determined projections. Adaptability measures the ability to adjust and cope with changes, reflecting the system's capacity for adaptation.

Projections were assessed w.r.t. three criteria given in Table 2.3, using the predefined scales. Plausibility and sustainability were assessed on a scale ranging from very low to very high within the interval of [0,100]. Adaptability, on the other hand, was

evaluated on a scale ranging from very high to very low within the interval of [0, 100]. The scale is reverse because exploring low adaptable projections is significant for the organizations. We aim to determine plausible scenarios as well as critical scenarios in terms of sustainability and adaptability. Individual criterion weights were assessed using a scale ranging from 0 to 1. To reduce the complexity of the assessments, a rating scale (no interaction (0), very low (0.2), low (0.4), medium (0.6), high (0.8), very high (1)) was used for criteria interactions as given in Table 2.3. Joint criteria weights were calculated using these assessments by Eq. 2.3 for three criteria and they were normalized because  $\mu_C (123)$  was not equal to 1. Criteria weights are given in Table 2.4.

**Table 2.2 : Factors and projections**

<b>Factors</b>	<b>Projections</b>
Travel Behavior of the Majority ( $ft_1$ )	Public transport ( $p_{11}$ ) Individual vehicles ( $p_{12}$ ) Bike, scooter etc. ( $p_{13}$ )
Car Ownership ( $ft_2$ )	Increasing ( $p_{21}$ ) Current state ( $p_{22}$ ) Decreasing ( $p_{23}$ )
Work Style ( $ft_3$ )	Remote work ( $p_{31}$ ) On-office ( $p_{32}$ )
Environmental awareness ( $ft_4$ )	High (voluntary) ( $p_{41}$ ) Medium (duty) ( $p_{42}$ ) Low ( $p_{43}$ )
Land Use ( $ft_5$ )	High urban centric jobs and housing ( $p_{51}$ ) High urban centric jobs and housing more dispersed ( $p_{52}$ ) High urban centric housing and jobs more dispersed ( $p_{53}$ )
New technologies for decarbonisation (Autonomous, electric vehicles etc.) ( $ft_6$ )	Limited ( $p_{61}$ ) Widespread ( $p_{62}$ )
Regulations and policies ( $ft_7$ )	Strict regulations for reducing usage of fossil fuel vehicles ( $p_{71}$ ) Current state ( $p_{72}$ )
Road Allocation ( $ft_8$ )	Road Allocations for bikes, scooters and public transports ( $p_{81}$ ) Current state ( $p_{82}$ )
Security (violence, harassment etc.) ( $ft_9$ )	High concern over security threats ( $p_{91}$ ) Low concern over security threats ( $p_{92}$ )
Connectivity of Public Transport ( $ft_{10}$ )	High in only central areas ( $p_{10,1}$ ) High in urban areas and limited in rural areas ( $p_{10,2}$ ) High in all areas ( $p_{10,3}$ )
Distribution of Wealth and Income ( $ft_{11}$ )	Inequality gap increases ( $p_{11,1}$ ) Inequality gap decreases ( $p_{11,2}$ )
Real Time Transportation Data ( $ft_{12}$ )	Highly improved ( $p_{12,1}$ ) Current state ( $p_{12,2}$ )

**Table 2.3 : Criteria assessment**

Criteria	Weights	Interactions	Assessments
Plausibility ( $\mu_1$ )	0.40	Plausibility and Sustainability ( $\mu_{12}$ )	Medium (0.60)
Sustainability ( $\mu_2$ )	0.50	Plausibility and Adaptability ( $\mu_{13}$ )	Low (0.40)
Adaptability ( $\mu_3$ )	0.20	Sustainability and Adaptability ( $\mu_{23}$ )	Very Low (0.20)
		All three criteria ( $\mu_{123}$ )	High (0.80)

To clarify how to obtain joint criteria weights, the calculation of  $\mu_{123}$  is given as  $\mu_{123} = \max(0.4 + 0.72 + 0.8 * 0.4 * 0.72; 0.5 + 0.632 + 0.8 * 0.5 * 0.632; 0.2 + 1.02 + 0.8 * 0.2 * 1.02) = 1.3848$ .

**Table 2.4 : Revised criteria weights**

Criteria (A)	Weights ( $\mu_A$ )	Normalized Weights ( $\mu_A^*$ )
1	0.40	0.289
2	0.50	0.361
3	0.20	0.144
1, 2	1.020	0.737
1, 3	0.632	0.456
2, 3	0.720	0.520
1, 2, 3	1.3848	1.000

Projection values were calculated using *ChI* and fuzzy measures as shown in Eq. 2.4. Assessments were aggregated to obtain a single overall value for each projection with respect to three criteria. The values are given in the last column of Table 2.5. As an example, the calculation for the projection “Public transport ( $p_{11}$ )” is given as follows:

$$\text{Since } f(x_3) < f(x_1) < f(x_2), \quad V_{p_{11}} = \sum_{u=1}^3 (f_{p_{11}}(x_u) - f_{p_{11}}(x_{u-1})) \mu_{A_u}^* = f(x_3) \mu_{123}^* + (f(x_1) - f(x_3)) \mu_{12}^* + (f(x_2) - f(x_1)) \mu_2^*. \quad V_{p_{11}} = 20 * 1 + (70 - 20) * 0.737 + (75 - 70) * 0.361 = 58.66.$$

Scenarios are quantified through the use of projection values. Initially, consistency values between projection pairs are needed. These values were assessed by experts on the scale [0, 1]. Considering the factors and projections, a total of 31,104 scenarios were generated. A scenario value was calculated for each of these using the Eq. 2.5.

The values of the entire set of scenarios were not provided due to the space limitation, yet an example calculation is provided for Scenario 1:

**Table 2.5 : Assessment and overall values of projections**

Projections	Plausibility	Sustainability	Adaptability	Overall Values
Public transport ( $p_{11}$ )	70	75	20	58.66
Individual vehicles ( $p_{12}$ )	60	75	35	58.84
Bike, scooter etc. ( $p_{13}$ )	55	60	25	48.92
Increasing ( $p_{21}$ )	40	70	60	54.01
Current state ( $p_{22}$ )	50	55	20	43.92
Decreasing ( $p_{23}$ )	55	75	45	59.59
Remote work ( $p_{31}$ )	50	45	40	45.13
On-office ( $p_{32}$ )	50	45	40	45.13
High (voluntary) ( $p_{41}$ )	40	65	30	46.40
Medium (duty) ( $p_{42}$ )	55	60	40	52.86
Low ( $p_{43}$ )	40	70	50	52.42
High urban centric jobs and housing ( $p_{51}$ )	45	50	60	49.04
High urban centric jobs and housing more dispersed( $p_{52}$ )	50	45	30	42.50
High urban centric housing and jobs more dispersed( $p_{53}$ )	30	60	35	41.63
Limited ( $p_{61}$ )	35	55	45	43.81
Widespread ( $p_{62}$ )	50	55	45	50.49
Strict regulations for reducing usage of fossil fuel vehicles ( $p_{71}$ )	60	75	40	60.16
Current state ( $p_{72}$ )	40	65	30	46.40
Road Allocations for bikes, scooters and public transports ( $p_{81}$ )	45	70	50	54.82
Current state ( $p_{82}$ )	35	60	30	42.71
High concern over security threats ( $p_{91}$ )	55	75	70	64.61
Low concern over security threats ( $p_{92}$ )	35	60	30	42.71
High in only central areas ( $p_{10,1}$ )	30	55	25	37.71
High in urban areas and limited in rural areas ( $p_{10,2}$ )	45	60	30	46.47
High in all areas ( $p_{10,3}$ )	45	65	40	50.91
Inequality gap increases ( $p_{11,1}$ )	60	55	65	57.45
Inequality gap decreases ( $p_{11,2}$ )	40	75	30	50.01
Highly improved ( $p_{12,1}$ )	70	60	40	57.63
Current state ( $p_{12,2}$ )	40	45	50	43.32

$$S_1 = [l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}, l_{11,1}, l_{12,1}],$$

$$\begin{aligned}
 SV_1 &= \sum_{\{p_{ij}, p_{yz}\} \in W} (V_{p_{ij}} + V_{p_{yz}}) con_{p_{ij}p_{yz}} = ((V_{p_{11}} + V_{p_{21}})con_{p_{11}p_{21}} + (V_{p_{11}} + \\
 &V_{p_{31}})con_{p_{11}p_{31}} + (V_{p_{11}} + V_{p_{41}})con_{p_{11}p_{41}} + \dots + (V_{p_{51}} + V_{p_{61}})con_{p_{51}p_{61}} + (V_{p_{51}} + \\
 &V_{p_{71}})con_{p_{51}p_{71}} + \dots + (V_{p_{10,1}} + V_{p_{12,1}})con_{p_{10,1}p_{12,1}} + (V_{p_{11,1}} + V_{p_{12,1}})con_{p_{11,1}p_{12,1}}) = \\
 &((58.66 + 54.01) \times 0.1 + (58.66 + 45.13) \times 0.3 + (58.66 + 46.40) \times 0.8 + \dots + \\
 &(49.04 + 43.81) \times 0.4 + (49.04 + 60.16) \times 0.4 + \dots + (37.71 + 57.63) \times 0.4 + \\
 &(57.45 + 57.63) \times 0.4) = 3251.68
 \end{aligned}$$

where the set  $W (\{\{p_{11}, p_{21}\}, \{p_{11}, p_{31}\}, \{p_{11}, p_{41}\}, \dots, \{p_{81}, p_{12,1}\}, \dots, \{p_{10,1}, p_{12,1}\}, \{p_{11,1}, p_{12,1}\}\})$  includes all pairs in Scenario 1.

Upon completion of the entire process, every scenario has a numerical value which makes them comparable. This is essential to have the ability to choose a number of influential scenarios in the future in order to take the necessary actions and precautions at present. In addition, selected scenarios should be different from each other to cover a wide range of future developments. Dissimilarity was used to measure the distance between all scenario pairs. For example, distance between  $S_1 = [l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}, l_{11,1}, l_{12,1}]$  and  $S_2 = [l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}, l_{11,1}, l_{12,2}]$  is  $\frac{1}{12}$ , since 11 projections are matched. All distances were calculated using Eq. 2.6 and considered as a parameter in the mathematical model. Scenario values were also represented as a parameter in the model. The experts established the remaining parameters as follows: the maximum number of scenarios (*MaxS*) was set at 4, the minimum distance between scenarios (*MinD*) was set at 0.55, and the threshold value (*TH*) was set at 3500, which falls between the third quartile and the maximum scenario value. The mathematical model was solved using Gurobi 9.5 with Python 3.8. The selected scenarios are given in Table 2.6.

The most prominent scenarios emerged as “Responsible Development”, “Efficient and Green”, “Individualist” and “Chaotic”. *Responsible Development*: The usage of fossil fuel cars has been limited and eco-friendly vehicles have increased. After the pandemic, the work style will significantly change. Although public transport is the major transportation mean, people will continue to use their own vehicles. According to the scenario "Efficient and Green", people’s environmental awareness will increase. They will prefer public transportation rather than individual vehicles, because public transport will become widespread not only in urban areas but also in rural areas. Technology will be adapted to both vehicles and urban transport systems. Security problems will be solved. According to the scenario "Individualist", regulations will be employed for fossil fuel cars. Environmental awareness will increase. However, car ownership will increase since there will be several problems such as security and road allocations. People will prefer individual vehicles due to the lack of necessary precautions to improve the urban transport system.

**Table 2.6 : Selected scenarios**

<b>Factors</b>	<b>Scenario 4326 (Scenario No.) (Responsible Development)</b>	<b>Scenario 7415 (Efficient and Green)</b>	<b>Scenario 13183 (Individualist)</b>	<b>Scenario 13322 (Chaotic)</b>
Travel behavior of the majority	Public transport	Public transport	Individual vehicles	Individual vehicles
Car ownership	Current state	Decreasing	Increasing	Increasing
Work Style	Remote work	Remote work	On-office	On-office
Environmental awareness	Medium (duty)	High (voluntarily)	Medium (duty)	Low
Land Use	High urban centric jobs and housing more dispersed	High urban centric housing and jobs more dispersed	High urban centric housing and jobs more dispersed	High urban centric jobs and housing
New technologies for decarbonisation	Widespread	Widespread	Widespread	Limited
Regulations and policies	Strict regulations for reducing usage of fossil fuel vehicles	Strict regulations for reducing usage of fossil fuel vehicles	Strict regulations for reducing usage of fossil fuel vehicles	Current state
Road allocation	Road allocations for bikes, scooters and public transports	Road allocations for bikes, scooters and public transports	Current state	Current state
Security	High concern over security threats	Low concern over security threats	High concern over security threats	High concern over security threats
Connectivity of public transport	High in urban areas and limited in rural areas	High in all areas	High in urban areas and limited in rural areas	High in only central areas
Distribution of wealth and income	inequality gap increases	inequality gap decreases	inequality gap decreases	inequality gap increases
Real time transportation data	Current state	Highly improved	Highly improved	Current state

According to the scenario "Chaotic", people will be unwilling to embrace new technologies and consider environmental impacts, resulting in a failure to implement essential measures for enhancing the urban transport system. Thus, people will turn to more individualistic options. These scenarios examined by area experts were found to be relevant and applicable.

The selected scenarios contain several opportunities and barriers. For example, with the increase in environmental awareness, the interest in public transportation has increased and car ownership has decreased or with the increase in individualism, car ownership and individual transport modes have increased. Actions should be taken for future developments which are seen as a barrier like high security concerns. According

to the selected scenarios, strategies for decarbonization of public transport system, feeder routes of different transport modes, traffic calming, integration of transfers, and technology usage in network management control centers can be developed. For example, parking regulations, congestion charging and neighborhood mobility centers can be established for the individualist scenario. The scenarios also show projections which can co-exist and are affected from each other. Specific projects can also be developed considering these projections.

## **2.4 Scenario Transfer**

Scenario transfer is an important phase for the practical usage of scenarios. Once the scenarios are selected, their contents, opportunities, and barriers are analyzed to set relevant objectives. Strategies are then developed to reach these objectives. However, other actors within the sector significantly influence these objectives, with existing power dynamics among them. Therefore, the MACTOR method is applied to identify potential allied and conflicted actors and develop strategies in alignment with allied actors to achieve the objectives effectively.

In the future transport application, four scenarios which were given in section 2.3 were selected. For “Responsible Development”, the objective could be an accessible, affordable, integrated and inclusive transportation system. Since car ownership may remain high with limited public transport in rural areas, dispersed housing, and transportation data behind the technological advances, the objective could be to create a system that ensures broad access to transportation which minimizes car dependency considering the strict regulations to reduce the use of fossil fuel vehicles. In the “Efficient and Green” scenario, the objective could be an environmentally sustainable transportation system. High environmental awareness is expected to drive public transport usage, reduce car ownership and facilitate the adoption of strict regulations. All developments in the scenario support the use of fossil-free fuel vehicles, bicycles, scooters and other eco-friendly modes of transportation, making it an ideal foundation for building a sustainable system. For the “Individualist” scenario, the focus could be on enhancing safety and security in travel. With a preference for personal vehicles, lower environmental awareness, and security concerns, a priority objective would be ensuring a safe and secure transportation system. In the “Chaotic” scenario, individual car use dominates, urban areas are densely populated, regulations are minimal, and

safe travel is not guaranteed. Inefficient transport links and road designs would lead to heavy congestion. Thus, the objective would be to reduce car dependency and manage traffic congestion to mitigate environmental impacts.

Achieving these objectives requires collaboration with influential actors such as municipalities, ministries, chambers of engineers, European Union. Therefore, actor-objective and actor-actor analyses should be conducted using the MACTOR method to identify potential collaborators and develop strategies. Details of this method are provided in Section 4.

## **2.5 Conclusion**

In this paper, a novel scenario planning approach is proposed for the evaluation and selection of scenarios. The approach provides a systematic framework for the whole process beginning with scenario development and ending with a manageable number of scenario selection. The advantage of the method is that it takes into account multiple criteria and the interaction between them, and also provides the selection of distinct scenarios representing the future space. The four scenarios that have been obtained reveal a valuable chance to identify potential opportunities, threats and challenges that may arise regarding future urban mobility system. This in turn facilitates the development of a long-term planning for building a sustainable and people oriented system. Also, strategic planners can make informed decisions regarding which strategies are most likely to be effective and sustainable in the long run by analyzing these scenarios and associated outcomes.

The study has some limitations that should be noted. Determining interactions among criteria may be complex as the number of criteria increases. For scenario planning, since there are not many criteria, the approach is useful and straightforward. However, it could be difficult to assess interactions for experts in some problems such as multi criteria decision making problems. Different methods or approaches can be developed when the criteria exceed five. Consistency is another limitation because only projection pairs are taken into account. For the joint occurrences of more than two projections, learning based methods can be utilized to extract from existing data.



### 3. A NOVEL APPROACH TO SCENARIO ASSESSMENT AND SELECTION<sup>2</sup>

In the information era, where technological advances and innovations shape our lives, organizations and societies need to adapt to rapid changes for survival. However, this is almost impossible without proper analysis of the environment (economic, technological, political, social and ecological) and consideration of the associated uncertainties and complexities. Therefore, foreseeing future changes and taking reasonable actions become necessary to survive in a highly competitive environment. These needs gave rise to the field of futures research (Gausemeier et al., 1998), which aims to explore future developments (Bengston, 2019). Various tools and methods including scenario planning, Delphi, trend impact, cross-impact, expert group meeting, multiple-equation models, futures wheel, futures polygon, and time series have been developed or used within the scope of futures research (Bengston, 2019; Gordon, 1992).

Scenario planning stands out as one of the most important and widely employed methods in futures research (Bishop et al., 2007). It supports the decision making process under risk and uncertainty at a strategic level and provides a systematic way to deal with the limited cognitive capacity of experts in the assessments regarding the examination of possible alternative futures (Amer et al., 2013; Stojanović et al., 2014). Scenario planning also enables organizations to be prepared for the future by foreseeing and managing opportunities and threats involved in alternative futures (Cornelius, Van de Putte, & Romani, 2005). Thus, the negative effects of impactful future events can be minimized as in the Shell case. Depending on the purpose of use and the research domain, the term “scenario” has been defined in different ways. Kahn defines scenario as a set of developed theoretical events to make causal events understandable (Kahn & Wiener, 1967). According to Tietje, scenario is a future state

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<sup>2</sup>This chapter is based on the paper (Accepted by Reviewers) “Yanmaz, O., & Asan, U. A novel approach to scenario assessment and selection. *International Journal of Information Technology & Decision Making*”

constructed by a combination of several factors (Tietje, 2005). There are also some definitions in the literature that specify what a scenario is not. For example, scenario is not a prediction (Gausemeier et al., 1998), preference (Cornelius et al., 2005) or a future reality (Durance & Godet, 2010).

A typical scenario planning process consists of the following stages (Godet, 1994; Schoemaker, 1995; Gausemeier et al., 1998; Polat & Asan, 2005; Saritas & Aylen, 2010; Sardesai, Stute, & Kamphues, 2021): i. “defining the decision field and formulating the scope of the problem, ii. determining key factors that deserve more attention in the future, iii. identifying future projections (i.e. levels) of the determined factors, iv. developing multiple scenarios and selecting a manageable subset of them, and v. transferring scenarios to strategies. The current study focuses on the relatively complex fourth stage of this process. Several studies have been suggested to improve the effectiveness and efficiency of the scenario development, assessment and selection process.

The development and assessment of scenarios may follow one of two distinct traditions: qualitative and quantitative. The qualitative approaches (such as the Scenario Matrix (Rhydderch, 2017) and the Wilson Matrix (Wilson, 1998) are generally regarded as highly subjective and biased (Favato & Vecchiato, 2017), and suffer from limited cognitive capacity of the experts (Hogarth, 1987) in considering several factors simultaneously. To address these issues, quantitative or semi-quantitative approaches have been introduced in forming complex scenarios. According to these approaches scenarios are developed through combinations of factor levels (Gausemeier et al., 1998; Tietje, 2005). Instead of assessing entire scenarios, the mentioned formulation simplifies the process by focusing on assessing individual factor levels and combining them into an overall score for each scenario. Essential in this assessment process are quality criteria (Kosow & Gaßner, 2008), also referred to as scenario validation criteria (Amer et al., 2013). Therefore, the specific criteria and the process through which these criteria are combined to derive the quality of each factor level need to be specified. Using quality criteria enhances the objectivity of scenario assessments and enables decision-makers to prioritize scenarios (Wilson, 1998; Tietje, 2005; Durance & Godet, 2010; Van der Heijden, 2011; Jahanishakib, Mirkarimi, Salmanmahiny, & Poodat, 2018) based on quantifiable metrics.

The common criteria used in the literature are probability, plausibility, consistency, novelty, comprehensibility, relevance, importance, transparency, completeness, diversity, desirability, coverage and tangibility (Amer et al., 2013). Several methods have been proposed to assess scenarios or factor levels using these criteria (Popper, 2008). However, even if these methods are effective tools and used in a wide range of application areas (Amer et al., 2013), they have several pitfalls. For example, a common criticism of the methods relying on probabilities is that it contradicts the main purpose of scenario planning, which surely is not to select the most likely factors or scenarios (Seeve & Vilkkumaa, 2022). In addition, it becomes often impractical to estimate conditional probabilities due to the multitude of factors involved (Bishop et al., 2007). Also, experts may assess probabilities based on the consistency among different factor levels (Grienitz, Hausicke, & Schmidt, 2014). Considering only plausibility or consistency in the assessment process is another point that has been criticized in the literature. Relying on plausibility may limit the extent of exploratory thinking (Crawford, 2019) while considering consistency alone might bring risk to exclude scenarios being representative (Wollenberg, Edmunds, & Buck, 2000). Similar criticism can be found in the literature for other quality criteria. A scenario having a lower value with respect to a criterion does not mean that this scenario may not occur. Therefore, using an assessment method based only on a single criterion may lead to a loss of information and, consequently, a poor representation of the alternative futures. There are also a few studies in the literature suggesting using more than one criterion (typically two) (Tietje, 2005; Lord et al., 2016; Seeve & Vilkkumaa, 2022). However, the suggested methods involve considering each criterion separately in different stages or steps of the assessment process. Since each criterion provides a specific lens through which the individual factor levels and their combinations are evaluated, it's important to strike a balance between different considerations (criteria) to enhance the quality and comprehensiveness of the assessment. Therefore, methods that consider multi-criteria simultaneously are needed to overcome these issues.

Another critical issue associated with the assessment process is the lack of studies that explicitly consider the interactions between criteria, which could be synergistic or antagonistic. Interaction is an important concept for futures research, since two criteria which seem unimportant may actually have a significant combined importance when they are considered jointly (Cigdem Kadaifci et al., 2020). An approach is needed that

allows for a more flexible representation of expert judgments, considering not only individual criteria but also their interactions in the assessment process. It should involve joint weights to quantify the significance of these interactions in influencing the overall value of factor levels.

Selecting a manageable number of scenarios is the final task of the fourth stage of the scenario planning process. This is necessary since the number of scenarios increases exponentially depending on the number of factors and factor levels. Without restricting the number of scenarios, the strategy development process based on scenarios may become very complex and hard to perform (Yanmaz & Asan, 2021). While there is no consensus on the ideal number of scenarios to choose, there is a tendency to opt for 3 to 6 scenarios (Amer et al., 2013). Several methods or procedures have been proposed in the scenario literature to select a final set of scenarios. Some of these methods eliminate the scenarios which include even a single implausible level pair (1998; Rhyne, 1981; Zwicky, 1967), while others perform a selection procedure which is based either on plausibility values or probability values of scenarios (Duperrin & Godet, 1975; Nguyen & Dunn, 2009). Alternatively, the methods considering two criteria perform elimination and selection procedures sequentially across distinct stages (Tietje, 2005; Lord et al., 2016; Seeve & Vilkkumaa, 2022). In the first stage, scenarios having lower consistency or plausibility values are filtered (Tietje, 2005). In the selection stage, methods are used to maximize the difference between scenarios that will be included in the final set to cover diverse futures (Tietje, 2005; Lord et al., 2016; Seeve & Vilkkumaa, 2022). Current studies lack a comprehensive model that simultaneously considers multiple constraints for optimum scenario selection and that gives experts the flexibility for altering necessary parameters. Therefore, an optimization model, whose aim is to select an optimum set of scenarios with respect to multiple constraints and criteria determined by experts and practitioners, is needed to solve this combinatorial problem rather than relying only on highly subjective and cognitively limited judgements.

To address the issues and research gaps outlined above, this study proposes a new approach that focuses on the assessment and selection stage of the scenario planning process. Scenarios are developed through combinations of factor levels, which, in contrast to existing literature, are assessed by experts based on multiple criteria. To be able to represent the weights of both individual and joint criteria a fuzzy measure is

suggested. Also, a quadratic programming model is introduced that ensures the obtained weight assessments to be consistent with fuzzy measure properties. This model serves also as an aggregation tool where individual expert assessments are combined into group assessments. To calculate the overall value of each factor level using the revised weights representing the importance of subsets of criteria, a nonlinear aggregation operator known as Choquet integral is employed. A new indicator called Scenario Value is introduced to represent the overall value of a scenario. It is obtained by combining the overall values of factor levels and the consistencies of level pairs constituting a particular scenario.

For the scenario selection step, a new mathematical model is developed that allows to obtain a manageable number of scenarios by solving a combinatorial problem. This will simplify the process of developing strategies based on alternative scenarios. The model explicitly considers the dissimilarity between scenario pairs as an additional criterion to select the most representative scenarios covering a wide range of alternative futures. To show how the final scenario set is obtained and to demonstrate the effectiveness and applicability of the proposed approach an application is provided.

The major contributions of the proposed approach can be listed as follows:

- To the best of our knowledge, this is the first time that multiple criteria are used simultaneously by considering their joint weights (i.e., interactions) to assess factor levels. For the calculations of the overall values of the factor levels Choquet integral is used, which permits to represent the interaction among criteria. The proposed approach effectively reduces possible loss of information and improves the comprehensiveness and accuracy of the scenario assessment and selection process.
- The joint weights can be obtained either qualitatively by using expert assessments or quantitatively by using mathematical approaches. If the qualitative approach is employed, experts may find it challenging and complex to assess the joint weights satisfying the measure properties. To address this difficulty, a quadratic programming model is proposed to revise the individual and joint weights of criteria provided by experts. This model also yields the aggregated assessments of experts.
- A new indicator is proposed to calculate the overall value of a scenario by combining overall values of factor levels (obtained by Choquet integral) and consistency values between level pairs. This indicator makes the scenarios comparable

and allows for an elimination process to filter scenarios that have lower overall value. Considering the Scenario Values, based on multiple criteria, instead of a criterion by criterion elimination process minimizes the loss of information.

- A new binary integer programming model is proposed to select a manageable number of scenarios that effectively represent a wide range of distinct futures. Considering distinct scenarios allows organizations to be better prepared for alternative futures and increases the robustness of the strategies they develop.
- Consequently, this study proposes the first semi-quantitative approach to deal with the scenario planning problem multi-dimensionally and simultaneously in terms of quality criteria. This contribution enriches the scenario planning literature where only a limited number of studies focus on method development for scenario assessment and selection (Amer et al., 2013).

The rest of the paper is organized as follows. Related works are presented in the following section. In sections three and four, the proposed methodology and the application are introduced, respectively. Sensitivity and comparative analysis are presented in sections 5 and 6. Finally, the conclusions and further research directions are presented in the last section.

### **3.1 Related Works**

The present study focuses on the assessment and selection of scenarios. To understand the challenges and research gaps this section reviews the most relevant studies on these topics.

Scenarios, which are representations of possible future developments, are typically qualitative in nature. In order to evaluate or analyze these scenarios effectively, they need to be translated into measurable terms. This means that the qualitative aspects of the scenarios need to be quantified or expressed in terms of specific metrics that can be objectively assessed or compared. Additionally, in order to simplify this process, concentrating on the assessment of individual factor levels rather than entire scenarios is more manageable and allows for clearer insights into the specific factors at play.

Various methods employ different quality criteria to assess factor levels or scenarios. The qualitative approaches based on expert judgments have suggested to use quality criteria such as plausibility, consistency, uncertainty, importance, novelty, relevance

or completeness (Bradfield et al., 2005; Amer et al., 2013). For example, the Scenario Matrix (i.e., four quadrants approach) involves pairing the two most important and uncertain factors related to the subject to serve as the basis for possible scenarios (Rhydderch, 2017). Similarly, the Wilson Matrix considers factors' uncertainty level and impact on the future (Wilson, 1998) in constructing scenarios. Morphological Analysis (MA) (Zwicky, 1967), on the other hand, uses plausibility for evaluating level pairs (Nguyen & Dunn, 2009). Especially the criteria relevance, completeness, transparency, and novelty, which are subjective, abstract, and hard to understand and evaluate, are avoided in quantitative methods. Instead, the common quantitative methods based on historic data extrapolation and Trend Impact Analysis (Gordon, 1994) use probability.

In semi-quantitative methods, which rely on analytical approaches using expert judgments, pairs of factor levels are commonly assessed with respect to criteria such as probability, plausibility, consistency, and diversity. For example, Field anomaly relaxation (FAR) (Rhyne, 1981), Optimized Linear Diversity Field Anomaly Relaxation (OLDFAR) (Lord et al., 2016) and Batelle approach (Geschka, Storvik, & Von Reibnitz, 1981) use plausibility for assessing level pairs (Zwicky, 1967; Lord et al., 2016). The Batelle approach subsequently computes scenario values through the averaging of level pairs or the consideration of the worst value. Cross impact analysis (Nguyen & Dunn, 2009; Wiek, Gasser, & Siegrist, 2009), on the other hand, uses marginal and conditional probabilities, considering causal relationships (Seeve & Vilkkumaa, 2022). The probability values must comply with some linear equations. Roponen and Salo (2023) utilize probability in the computation of scenario probabilities through cross-impact multipliers. In a more recent study, the same authors use probabilities to construct Bayesian networks that allows for what-if analyses (Roponen & Salo, 2023). Another group of studies including Seeve and Vilkkumaa (2022), Wiek et al. (2009), Spielmann et al. (2005), Tietje (2005), and Gausemeier (1998) focus on consistency between level pairs. While Wiek et al. and Spielmann et al. aggregate consistencies of level pairs to derive scenario consistency value, Seeve and Vilkkumaa use average consistency as a scenario value indicator. Tietje introduces several indicators such as additive consistency, multiplicative consistency, number of inconsistency, and minimum consistency level based on predefined scales. Tietje (2005), Lord et al. (2016) and Seeve and Vilkkumaa (2022)

consider diversity as an additional criterion to represent distinct futures as much as possible.

Although the studies and methods outlined above offer an improved approach for the development and assessment of scenarios and thereby a richer representation of the future, they typically carry out scenario or factor level assessments relying on just one or, at most, two criteria. Moreover, none of them consider multiple criteria simultaneously and they completely disregard the interaction among criteria (i.e., joint weighting).

The next step of the scenario planning process involves combining factor levels to obtain scenarios. When all possible combinations are taken into account, a large number of scenarios are generated. Since reducing the number of scenarios will improve the effectiveness and efficiency of strategy development, a smaller, more manageable set of scenarios needs to be selected. This selection process involves either eliminating certain scenarios through predefined rules or employing specific techniques to select a set of scenarios. MA (Zwicky, 1967), FAR (Rhyne, 1981) and the method proposed by Gausemier et al (1998). eliminate the scenarios which include even a single implausible level pair, while the Battelle approach performs a selection procedure which is based either on the average plausibility value or the worst plausibility value of scenarios (Nguyen & Dunn, 2009). Cross impact (Sarin, 1978) ranks scenario probabilities of scenarios and chooses a subset consisting of the most probable ones. The main weakness of these methods is that they consider only a single criterion to eliminate or select scenarios.

On the other hand, Gausemier et al. (1998) employ a two-step approach wherein scenarios containing completely inconsistent pairs are removed and the remaining ones clustered to determine a manageable number of scenarios. A similar procedure is followed by Wiek et al. (2009) where they initially filter scenarios based on inconsistent pairs and a predetermined consistency threshold, and then utilize a cluster analysis to introduce a diversity index for selecting a subset of scenarios characterized by high diversity. Spielmann et al. (2005) opt for a scenario set characterized by high consistency scores, no inconsistencies, and diversity. Seeve and Vilkkuma (2022) initiate the scenario elimination process by excluding those with low consistency values, and subsequently, from the remaining scenarios, employ the weighted set covering problem to select a scenario set that covers all factor levels. Tietje (2005)

also employs a two-stage approach, excluding scenarios with inconsistent factor level pairs or a consistency level below a minimum threshold. Following this, one of three distinct scenario selection procedures is used: local efficiency, distance-to-selected, and max-min-selection (Tietje, 2005). The author defines a distance indicator, with all three procedures being based on it. For instance, in the third procedure, a minimum distance is established. The scenario with the maximum consistency value is chosen initially, and the scenario with the highest consistency value among the remaining unselected scenarios becomes the test scenario. If the distance of the test scenario to all selected scenarios exceeds the minimum distance, it joins the scenario set. This iterative process continues until no more scenarios are selected or tested. Mazzorana and Fuchs (2010) uses Tietje's approach in combination with fuzzy set theory to enhance knowledge representation. In another study, Mazzorana et al. (2012) extends Tietje's approach by incorporating a third step where probabilities are assigned to the selected scenarios. In a study based on plausibility, Lord et al. (2016) introduce an optimization technique to select a small but maximally diverse subset of scenarios from a multi-dimensional morphological analysis. Apart from the previous mentioned studies, Wu et al. (2011) suggest a 0-1 integer programming model to help decision makers select scenarios in software development to minimize cost and maximize reliability while satisfying system requirements to a certain degree. Overall, the methods considering two criteria perform elimination and selection processes consecutively in different stages (Tietje, 2005; Lord et al., 2016; Seeve & Vilkkumaa, 2022). In the first stage, scenario consistency (or plausibility) values are calculated using either additive, multiplicative or similar indicators. A set of scenarios is constructed by filtering scenarios having lower consistency (or plausibility) values (Seeve & Vilkkumaa, 2022) or scenarios whose consistency (or plausibility) values are lower than a threshold value (Tietje, 2005). In the selection stage, rule-based, clustering-based or optimization-based methods are used to minimize the number of scenarios and maximize the difference between scenarios that will be included in the final set (Tietje, 2005; Lord et al., 2016; Seeve & Vilkkumaa, 2022).

Consequently, the existing literature does not offer a comprehensive model that simultaneously accounts for multiple constraints in optimal scenario selection while providing decision makers with the flexibility to adjust essential parameters. Therefore, there is a need for an optimization model aimed at selecting an optimal set

of scenarios based on multiple constraints and criteria to solve this combinatorial problem.

To address these needs, this study proposes a new approach that concentrates on the assessment and selection stage of the scenario planning process, which details are provided in the following sections.

## **3.2 Proposed Methodology**

### **3.2.1 Mathematical basis of the proposed approach**

The measure, which is used for assigning values to particular sets and generalizes length, area and volume (Torra, Narukawa, & Sugeno, 2013), is a substantial concept in mathematics (Murofushi & Sugeno, 2000). Two prominent examples of the measure are Probability and Lebesgue measures (Torra et al., 2013). The main characteristic of these measures is the additivity property (Murofushi & Sugeno, 2000). Although additivity is useful for some applications, it is inconvenient for many real-world problems especially multi-criteria decision making (MCDM) problems since it does not consider synergy or interaction between elements of a system (Maleki, Gholamian, & Yaghoubi, 2022). To address this issue, fuzzy measure was proposed by Sugeno (1974). Note that the fuzzy measures are named by the researchers differently such as non-additive measure (Denneberg, 1994) and capacity (Choquet, 1954). Fuzzy measure is important to represent uncertainty involved in the information (Yager, 2020) and synergy between elements (Kacprzyk, Sirbiladze, & Tsulaia, 2022). For example, the total performance of a sports team may not be equal to the sum of individual performances. A negative or positive synergy between players may occur.

For example, suppose that we evaluate different alternative future scenarios using the criteria Adaptability and Importance. Adaptability describes that the company can easily adapt to a future scenario, while Importance describes that a future scenario has a critical impact on the company's success. Now consider a future scenario where adaptability is low and importance is high. Low adaptability suggests that the company struggles to adapt to changes in the environment. This could be due to factors like rigid organizational structures or a lack of resources to implement necessary changes. High importance indicates that the scenario has a critical impact on the company's success. This could be due to factors such as new market opportunity, technological

advancements, or regulatory shifts that greatly influence the company's future prospects. In an additive model, the overall value of the future scenario would be expressed as the sum of the individual values for Adaptability and Importance. However, the decision maker might believe that when adaptability is low, the high importance of the scenario exacerbates the negative impact on the overall value. If the company is unable to adapt to changing market conditions (low adaptability), even a scenario of high importance (e.g., a new market opportunity) may not translate into success due to the company's limitations in responding and adjusting. This could represent a situation where the critical importance of a scenario is severely compromised due to the company's inability to adapt effectively. The negative synergy implies that the joint consideration of these conditions has a more adverse impact on the overall value than would be expected based on their individual contributions. This illustrates how a nonadditive model can capture negative synergies and provide a more nuanced representation of decision maker preferences in evaluating future scenarios.

Highlighting the importance of considering the synergy effects among criteria, this approach leads to a more accurate representation of real-life scenarios. By acknowledging the interactions between different criteria, we can enhance the precision and reliability of results in practical problem-solving situations. Hence, incorporating the concept of synergy is imperative for achieving more nuanced and realistic outcomes in decision-making processes.

Fuzzy measure is defined as follows:

**Definition 1 (Michio Sugeno, 1974):** Let  $X$  be a finite set and a fuzzy measure  $\mu$  defined on  $X$  be a set function  $\mu: P(X) \rightarrow [0,1]$ , where  $P(X)$  is power set of  $X$ . It has following properties:

- iii. Boundary,  $\mu(\emptyset) = 0, \mu(X) = 1$ .
- iv. Monotonicity,  $\mu(A) \leq \mu(C)$  if  $A \subseteq C$ .

When positive synergy exists among elements, it is expressed by  $\mu(A \cup B) > \mu(A) + \mu(B)$ , and for negative synergy, the inequality becomes  $\mu(A \cup B) < \mu(A) + \mu(B)$ , where  $A, B \subset X$ .

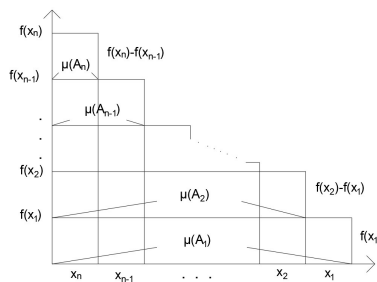
### 3.2.1.1 Choquet integral

Choquet integral (ChI), proposed by Gustave Choquet (1954), is a nonlinear aggregation operator based on fuzzy measure (Islam, Anderson, Pinar, & Havens, 2017). It is used to combine uncertain information and produces a single value (Haile, 2017). The main feature of the ChI is representing the interaction between elements of a system (Mohamed & Xiao, 2003). Due to this feature, it has been used in many applications such as regression (Du & Zare, 2018), classification (Grabisch, 2000; Yang, Wang, Heng, & Leung, 2007), cross-impact analysis (Cigdem Kadaifci et al., 2020), and pattern recognition (Fang, Rizzo, Wang, Espy, & Wang, 2010; Karczmarek, Kiersztyn, & Pedrycz, 2018). Besides, in decision making problems (Grabisch, 1996; Demirel, Demirel, & Kahraman, 2010; Tehrani, Cheng, & Hullermeier, 2012; Chen, Duan, Wang, & Ma, 2020) ChI is commonly used to calculate the aggregated value of an alternative with respect to several criteria which are correlated. Thus, joint effects of criteria are considered in the calculation process of the aggregated values (Grabisch, 1997). For this reason, ChI is a more powerful tool than other well-known aggregation operators like arithmetic means, weighted sum and ordered weighted averaging (OWA). Moreover, the use of ChI provides more accurate results in practice (Chen et al., 2020).

Definition 2 (Choquet, 1954; Kadaifci et al., 2020): Let  $\mu$  be a fuzzy measure on the set  $X = \{x_1, x_2, x_3, \dots, x_n\}$ . The ChI of a function  $f: X \rightarrow [0, \infty]$  w.r.t. fuzzy measure  $\mu$  is defined as:

$$\int f d\mu = \sum_{i=1}^n (f(x_i) - f(x_{i-1}))\mu(A_i) \quad (3.1)$$

where the indices  $i = 1, 2, 3, \dots, n$  represents the position of permuted function  $0 \leq f(x_1) \leq f(x_2) \leq f(x_3) \leq \dots \leq f(x_n)$ ,  $f(x_0) = 0$  and  $A_i \subseteq X$ . Graphical representation of Choquet integral is given in Figure 3.1:



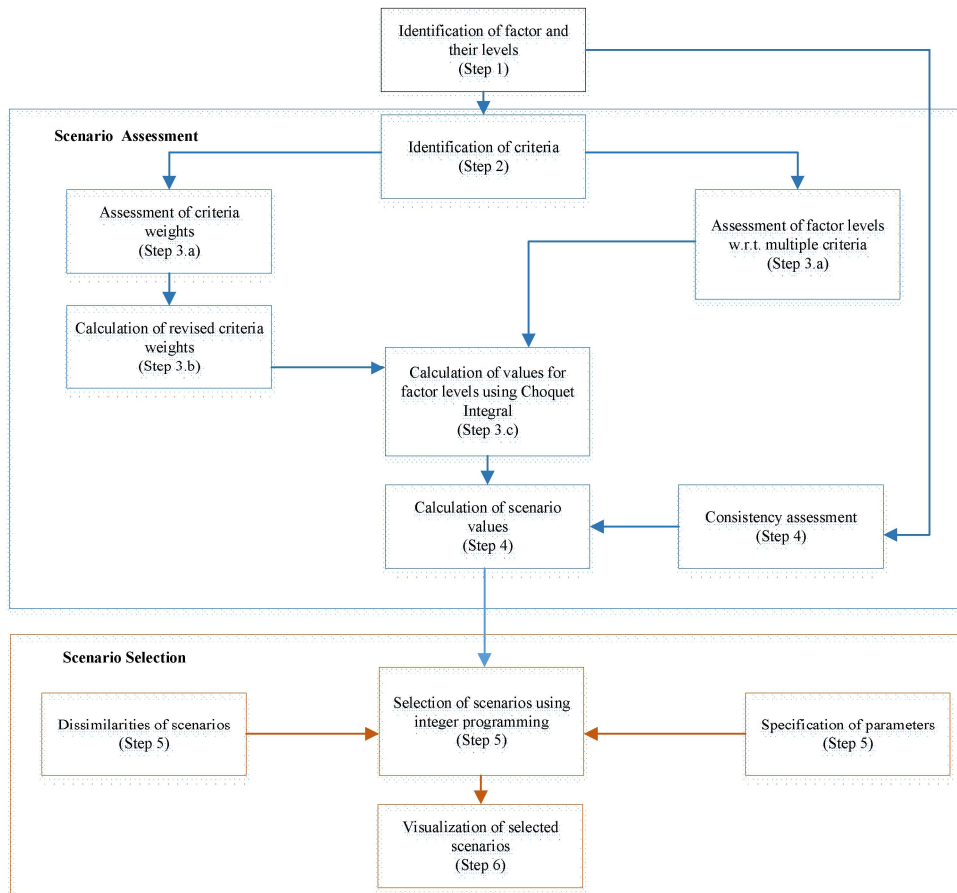
**Figure 3.1 :** Graphical representation of ChI.

### 3.2.2 Proposed approach

The proposed approach fundamentally consists of three stages: assessment of factor levels, calculation of scenario values and selection of final scenarios (see in Figure. 3.2). Since scenarios involve the combinations of a large number of factor levels, evaluating them as a whole is impractical. Instead, the factor levels are assessed and aggregated to represent the scenario itself. Factor levels are assessed with respect to multiple criteria and the assessments are aggregated using Choquet integral to obtain an overall value of each factor level considering the interaction among the criteria. The Choquet integral is an effective tool to aggregate assessments considering both criteria and their interactions in addition to overcoming the lack of representation issue of the additivity property in real-life problems. To ensure that the scenarios are measurable and thereby comparable, the aggregated values and consistencies between level pairs are combined to obtain the overall scenario values as inputs to the scenario selection stage. In the final stage, a binary integer programming model is developed to determine the final scenario set consisting of a small number of scenarios by maximizing the weighted sum of the dissimilarity between scenarios and scenario values to be included in the final scenario set. The steps of the proposed approach are explained in detail with the help of a simple example application about Australia's regional environment in 2030 which is crucial in determining the strategic plans of Australia's Defense Force (Nguyen & Dunn, 2009). Note that the only data used in this paper are the factors and their levels. The assessments are randomly generated.

Scenarios are described as possible states of a system in the future and they are represented by means of factor levels (Tietje, 2005). Simply, a scenario is a combination of levels of these factors. The steps of the proposed approach are explained below.

Definition 3: Let  $F$  be a set of factors denoted by  $F = \{f_{c_1}, \dots, f_{c_I}\}$  and  $f_{c_i} \in F$  be a set of levels of factor  $i$  denoted by  $f_{c_i} = \{l_{i1}, \dots, l_{ij}\}$ , i.e.  $l_{ij} \in f_{c_i}$ , where factor indices  $i = 1, \dots, I$  and level indices  $j = 1, \dots, J$ . Each factor may have a different number of levels. Then a scenario, that is constructed by selecting one level from each factor, is represented as a vector of a combination of factor levels  $S_k = [l_{1j} \dots l_{Ij}]$ , where scenario indices  $k = 1, \dots, K$ . All combinations of levels construct a scenario set  $S = \{S_1, \dots, S_K\}$ . The cardinality of the scenario set is calculated as  $K = |S| = \prod_i |f_{c_i}|$ .



**Figure 3.2 :** Framework of the proposed approach.

**Step 1. Identification of factors and their levels:** Factors and levels, which are relevant to the application area, are determined based on expert opinions and literature review. Factors and their levels in the example, given in Table 3.1, constitute 36 scenarios ( $K = 2 \times 3 \times 2 \times 3$ ). One of the scenarios consisting of a stable political environment, collapsing economy, conflict between groups and sustainable habitat is denoted by  $S_{16} = [l_{11} \ l_{23} \ l_{32} \ l_{41}]$ .

**Table 3.1 :** Factor and their levels.

Factor	Level
Political Governance ( $fc_1$ )	Stable environment ( $l_{11}$ )
	Unstable environment ( $l_{12}$ )
Economic Growth ( $fc_2$ )	Developing ( $l_{21}$ )
	Declining ( $l_{22}$ )
	Collapse ( $l_{23}$ )
Social Cohesion ( $fc_3$ )	Tolerance between groups ( $l_{31}$ )
	Conflict between groups ( $l_{32}$ )
Health and Habitat ( $fc_4$ )	Sustainable ( $l_{41}$ )
	Degradation ( $l_{42}$ )
	Collapse ( $l_{43}$ )

**Step 2. Identification of criteria:** The relevant criteria to measure scenario quality are selected among the existing criteria in the literature or a new criterion can be identified by the researchers.

Definition 4: Let  $X$  be a set of criteria. The set is denoted by  $X = \{x_1, \dots, x_U\}$ , where  $x_u \in X$  is a criterion and indices  $u = 1, \dots, U$ .

In the example, five criteria, namely plausibility ( $x_1$ ), significance ( $x_2$ ), adaptability ( $x_3$ ), consistency ( $x_4$ ) and dissimilarity ( $x_5$ ), are determined. Definitions of the criteria are given in Table 3.2.

**Table 3.2 : Definitions of criteria.**

Criteria	Definition
Plausibility	The degree of being capable of happening
Significance	To what extent the levels are affecting the industry
Adaptability	The organization's adaptation capability
Consistency	The degree of coexistence of the factor levels
Dissimilarity	Dissimilarity between scenarios

**Step 3. Evaluation of factor levels with respect to multiple criteria:** Factor levels, which are qualitative by nature, are required to be evaluated with respect to the selected criteria for obtaining values for each. Three criteria, plausibility, significance and adaptability, are used in this step. Consistency and dissimilarity will be used in the following steps. The sub-steps are described below:

**a.** Assessment of criteria weights and factor levels: Assessments are made by experts working in the application area. Note that an MCDM method can be utilized to obtain criteria weights. Since the primary concern of this study is not obtaining criteria weights, they are collected directly from experts on a pre-defined scale. The individual and joint criteria weights as well as assessments of factor levels, which were specified arbitrarily for the illustrative example, are given in Table 3.3 and Table 3.4, respectively. The scales used in the example are  $[0, 1]$  for criteria weights and  $[0, 100]$  for factor levels. We may assume that zero represents ease of adaptability while it becomes more difficult to adapt to the environment when the scale value increases. On the other hand, the greater the scale value, the higher the significance and plausibility of the factor level.

**Table 3.3 : Criteria weights.**

Criteria	Weights
Plausibility	0.40
Significance	0.20
Adaptability	0.30
Plausibility and Significance	0.75
Plausibility and Adaptability	0.60
Significance and Adaptability	0.50

**Table 3.4 : Assessment values of factor levels.**

Level	Plausibility	Significance	Adaptability
Stable environment ( $l_{11}$ )	15	43	3
Unstable environment ( $l_{12}$ )	6	42	41
Developing ( $l_{21}$ )	10	41	5
Declining ( $l_{22}$ )	31	30	30
Collapse ( $l_{23}$ )	49	21	4
Tolerance between groups ( $l_{31}$ )	27	23	37
Conflict between groups ( $l_{32}$ )	25	1	12
Sustainable ( $l_{41}$ )	42	36	33
Degradation ( $l_{42}$ )	14	18	3
Collapse ( $l_{43}$ )	59	71	14

**b.** Calculation of revised criteria weights: As stated above, individual and joint criteria weights, which are represented by fuzzy measures ( $\mu$ ), are evaluated by a group of experts. Since the assessments are based on subjective perception, it is practically very hard to assess all weights meeting the fuzzy measure properties for experts because of their limited cognitive capacity. Another issue related to the weights is reaching a compromise between differing expert assessments. Therefore, the assessments should be revised to obtain proper values that are consistent with the fuzzy measure properties. A quadratic programming model, which is based on minimizing the total deviation between expert and revised assessments, is introduced to handle these problems. Since the model is expected to revise the criteria weights, the signs of the corresponding weights direction of the relationships (i.e. the positive or negative synergy) among all subsets of the criteria set are provided by experts. The collected information regarding the signs is incorporated into the model in the form of constraints.

Definition 5: Let  $X = \{x_1, x_2, x_3, \dots, x_U\}$  be a finite set of criteria and  $I_C \in \{-1 \text{ (negative synergy), } 1 \text{ (positive synergy)}\}$  be the sign of the synergy, where the set  $C \subseteq X$ . When there is a positive synergy ( $I_C = 1$ ), the inequality  $\mu(A) + \mu(B) \leq \mu(C)$  must be satisfied, where  $\forall A, B \subset C$  and  $A \cap B = \emptyset$ , while for negative synergy ( $I_C = -1$ ) the inequality  $\mu(A) + \mu(B) \geq \mu(C)$  must be satisfied.

The general model is given below.

Indices:

$u$ : criteria indices (1, ...,  $|X|$ )

$d$ : expert indices (1, ...,  $|D|$ )

Parameters:

$\mu_A^d$ : criteria assessments of set  $A$  by expert  $d$ , where  $\mu(A) = \mu_A, \forall A \subseteq X$  and  $\mu_X^d = 1$

$I_C$ : sign of the synergy of the set  $C$

Decision variable:

$\hat{\mu}_A$ : revised criteria weights of set  $A$

Quadratic programming model:

$$\text{Min} \sum_{A \subseteq X} \sum_d^D (\hat{\mu}_A - \mu_A^d)^2 \quad (3.2)$$

$$\hat{\mu}_A \geq 0 \quad \forall A \subseteq X, |A| = 1 \quad (3.3)$$

$$\hat{\mu}_A \leq \hat{\mu}_{A \cup u} \quad \forall A \subset X, 1 \leq |A| \leq |X| - 1 \text{ and } \forall u \in X, \forall u \notin A \quad (3.4)$$

$$\begin{aligned} I_C(\hat{\mu}_C - (\hat{\mu}_A + \hat{\mu}_B)) \\ \geq 0 \end{aligned} \quad \forall C \subseteq X, \forall A, B \subset C, 1 \leq |A| \leq |B| < |C| \leq |X|, A \cap B = \emptyset \quad (3.5)$$

In the solution of the model, if  $\hat{\mu}_X \neq 1$ , then the revised criteria weights are normalized with the equation  $\hat{\mu}_A^* = \frac{\hat{\mu}_A}{\hat{\mu}_X}$ , where  $\forall A \subseteq X$ .

The objective function minimizes the sum of squared deviations between revised values and expert assessments (Eq. 3.2). Eq. 3.3 ensures that individual criteria weights are greater than zero (i.e.  $\hat{\mu}_1 \geq 0$ ). Eq. 3.4 satisfies the monotonicity property (i.e.  $\hat{\mu}_1 \leq$

$\hat{\mu}_{12}, \hat{\mu}_2 \leq \hat{\mu}_{12}$ ), while Eq. 3.5 is the synergy inequality (i.e. for  $I_{12} = 1$ , the constraint becomes  $\hat{\mu}_{12} \geq \hat{\mu}_1 + \hat{\mu}_2$ ).

In the example, the set  $X = \{x_1, x_2, x_3\}$  consists of three criteria where the weights are  $\mu_1^1 = \mu(x_1) = 0.4, \mu_2^1 = 0.2, \mu_3^1 = 0.3, \mu_{12}^1 = 0.75, \mu_{13}^1 = 0.60, \mu_{23}^1 = 0.50$ , and  $\mu_{123}^1 = 1$ . Signs of the synergies are  $I_{12} = 1, I_{13} = -1, I_{23} = 1$ , and  $I_{123} = -1$ . The solution of the model based on given parameters is  $\hat{\mu}_1 = 0.4, \hat{\mu}_2 = 0.25, \hat{\mu}_3 = 0.275, \hat{\mu}_{12} = 0.75, \hat{\mu}_{13} = 0.675, \hat{\mu}_{23} = 0.525, \hat{\mu}_{123} = 0.925$ . Since  $\hat{\mu}_{123}(\hat{\mu}_X)$  is not equal to 1, values are normalized with  $\hat{\mu}_A^* = \frac{\hat{\mu}_A}{\hat{\mu}_X}$ . Normalized values become  $\hat{\mu}_1^* = 0.43, \hat{\mu}_2^* = 0.27, \hat{\mu}_3^* = 0.30, \hat{\mu}_{12}^* = 0.81, \hat{\mu}_{13}^* = 0.73, \hat{\mu}_{23}^* = 0.57, \hat{\mu}_X^* = 1$ .

**c.** Calculation of values for factor levels: The assessments of the factor levels are required to be aggregated considering joint criteria weights. The aggregated values for each factor level with respect to the criteria are calculated using ChI as in Eq. 3.6.

Definition 6: Let  $f_{l_{ij}}(x_u)$  be the value of factor level  $l_{ij}$  w.r.t. criterion  $x_u$  and  $V_{l_{ij}}\{x_1, x_2, x_3\}$  (i.e.  $V_{l_{ij}}$ ) be the aggregated value of factor level  $l_{ij}$  w.r.t. criteria  $x_1, x_2$  and  $x_3$ .

The notations in Eq. 2.1 are modified as follows considering the structure of the proposed approach:

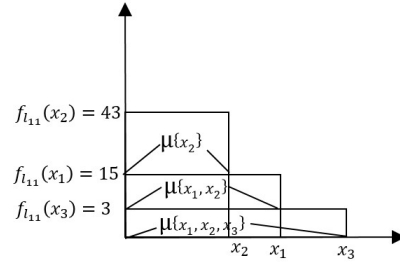
$$V_{l_{ij}} = \sum_{u \in Su} \left( f_{l_{ij}}(x_u) - f_{l_{ij}}(x_{u-1}) \right) \hat{\mu}_{A_u}^* \quad (3.6)$$

where  $Su$  is the sorted set of criteria w.r.t. level values in increasing order.

For the level  $l_{11}$  (stable environment), assessments are  $f_{l_{11}}(x_1) = 15, f_{l_{11}}(x_2) = 43, f_{l_{11}}(x_3) = 3$ . The calculations are clarified below while the graphical representation is demonstrated in Fig. 3.3.

$$\begin{aligned} V_{l_{11}} &= f_{l_{11}}(x_3) \hat{\mu}_{\{x_1, x_2, x_3\}}^* + \left( f_{l_{11}}(x_1) - f_{l_{11}}(x_3) \right) \hat{\mu}_{\{x_1, x_2\}}^* \\ &\quad + \left( f_{l_{11}}(x_2) - f_{l_{11}}(x_1) \right) \hat{\mu}_{\{x_2\}}^* \end{aligned}$$

$$V_{l_{11}} = 3 \times 1 + (15 - 3) \times 0.81 + (43 - 15) \times 0.27 = 20.28$$



**Figure 3.3 :** Graphical representation of the calculation of ChI.

Accordingly, the aggregated values of factor levels are obtained as shown in Table 3.5.

**Table 3.5 :** Aggregated values of factor levels.

Level	$V_{l_{ij}}$
$l_{11}$	20.28
$l_{12}$	26.22
$l_{21}$	17.42
$l_{22}$	30.43
$l_{23}$	29.81
$l_{31}$	28.92
$l_{32}$	14.62
$l_{41}$	38.01
$l_{42}$	12.99
$l_{43}$	53.69

**Step 4. Calculation of scenario values:** At this step, the consistency assessments are included in the aggregated values of factor levels to obtain the overall scenario values. Consistency measures the degree of coexistence of factor levels. To ensure the representativeness, all possible combinations of factor levels should be considered. Since the number of combinations grows exponentially as the number of factor levels increases, higher order coexistences are omitted and only the consistencies of level pairs are considered. Consistencies between level pairs are assessed by experts on the scale [0 1]. The proposed indicator to combine the aggregated values and consistencies is given in Eq. 3.7.

**Definition 7:** Let  $c_{l_{ij}l_{pr}}$  be a consistency value for the level  $l_{ij}$  and  $l_{pr}$  in scenario  $k$ , where indices  $i$  and  $p$  for factors, and indices  $j$  and  $r$  for factor levels. Let  $SV_k$  be the value for scenario  $k$ . The proposed equation for aggregation is given as follows:

$$SV_k = (\sum_{\{l_{ij}, l_{pr}\} \in W} (V_{l_{ij}} + V_{l_{pr}}) c_{l_{ij}l_{pr}}) / (I - 1) \quad (3.7)$$

where the set  $W$  contains all two elements subsets of the set consisting of all levels involved in scenario  $k$ .

For the example, the first scenario is  $S_1 = [l_{11} l_{21} l_{31} l_{41}]$ . The set  $W = \{\{l_{11}, l_{21}\}, \{l_{11}, l_{31}\}, \{l_{11}, l_{41}\}, \{l_{21}, l_{31}\}, \{l_{21}, l_{41}\}, \{l_{31}, l_{41}\}\}$ . The value of scenario 1 is calculated by utilizing the consistency values arbitrarily specified in Table 3.6 as follows:

$$\begin{aligned} SV_1 &= ((V_{l_{11}} + V_{l_{21}})c_{l_{11}l_{21}} + (V_{l_{11}} + V_{l_{31}})c_{l_{11}l_{31}} + (V_{l_{11}} + V_{l_{41}})c_{l_{11}l_{41}} \\ &\quad + (V_{l_{21}} + V_{l_{31}})c_{l_{21}l_{31}} + (V_{l_{21}} + V_{l_{41}})c_{l_{21}l_{41}} + (V_{l_{31}} + V_{l_{41}})c_{l_{31}l_{41}}) / 3 \\ &= ((20.28 + 17.42) \times 0.44 + (20.28 + 28.92) \times 0.12 \\ &\quad + (20.28 + 38.01) \times 0.16 + (17.42 + 28.92) \times 0.97 \\ &\quad + (17.42 + 38.01) \times 0.52 + (28.92 + 38.01) \times 0.49) / 3 = 45.87 \end{aligned}$$

**Table 3.6 :** Consistency values of level pairs.

	$l_{11}$	$l_{12}$	$l_{21}$	$l_{22}$	$l_{23}$	$l_{31}$	$l_{32}$	$l_{41}$	$l_{42}$	$l_{43}$
$l_{11}$	0	0	0.44	0.58	0.63	0.12	0.98	0.16	0.91	0.97
$l_{12}$	0	0	0.59	0.63	0.96	0.91	0.37	0.97	0.20	0.86
$l_{21}$	0.44	0.59	0	0	0	0.97	0.56	0.52	0.30	0.66
$l_{22}$	0.58	0.63	0	0	0	0.91	0.21	0.09	0.35	0.68
$l_{23}$	0.63	0.96	0	0	0	0.41	0.03	0.31	0.15	0.99
$l_{31}$	0.12	0.91	0.97	0.91	0.41	0	0	0.49	0.45	0.24
$l_{32}$	0.98	0.37	0.56	0.21	0.03	0	0	0.26	0.69	0.04
$l_{41}$	0.16	0.97	0.52	0.09	0.31	0.49	0.26	0	0	0
$l_{42}$	0.91	0.20	0.30	0.35	0.15	0.45	0.69	0	0	0
$l_{43}$	0.97	0.86	0.66	0.68	0.99	0.24	0.04	0	0	0

**Step 5. Selection of a small number of scenarios:** As aforementioned, scenarios are useful tools to develop strategies. Yet, considering all possible scenarios is not manageable and reasonable even though an elimination procedure based on selected quality criteria is performed. Obtaining the overall scenario values in the previous stages enables a comparison among the scenarios, as well as interpretation regarding the content of scenarios. But, the overall value itself does not guarantee to span a wide range of future developments due to the uncertainty involved in the future. Therefore, scenarios that best cover the future and also meet certain constraints in terms of criteria

should be selected. Accordingly dissimilarity ( $x_5$ ), is defined to measure the difference between qualitative scenarios.

Definition 8: Let  $D_{kt}$  be the dissimilarity (i.e. distance) value between scenario  $k$  and scenario  $t$ , where scenario indices  $k, t = 1, \dots, K$ . The measure for the dissimilarity is defined as (Prasetyo & Purwarianti, 2014):

$$D_{kt} = \frac{l-m}{l} \quad (3.8)$$

where  $l$  is the number of factors and  $m$  is the number of factor levels which match in scenario  $k$  and scenario  $t$ .

The distance between the scenarios  $S_1 = [l_{11} \ l_{21} \ l_{31} \ l_{41}]$  and  $S_{16} = [l_{11} \ l_{23} \ l_{32} \ l_{41}]$  in the example is  $D_{1,16} = 0.5$  where  $l = 4$  and  $m = 2$  ( $l_{11}$  and  $l_{41}$ ).

A binary integer programming model is proposed to select a combination of scenarios that are dissimilar and also have greater values than a threshold value with respect to criteria. Because selecting a small number of scenarios satisfying the determined criteria allows to be prepared for alternative futures.

Definition 9: Let  $w_k$  be the normalized value of scenario  $k$ . To obtain  $w_k$ , the value of scenario  $k$  is divided by the sum of the two largest scenario values to ensure the sum of the weights of the selected scenario pairs should not exceed one. As the first part of the objective function can take values in the interval  $[0,1]$ , this normalization enables the second part to be in the same interval. The sum of  $y$  largest elements is defined by Eq. 3.9 (Todd, 2018). This equation is adapted to the sum of the two largest elements as given in Eq. 3.10, which corresponds to the normalized value of scenario  $k$ .

$$T^y(SV) = \max_{|Y|=y, Y \subset Sn} \sum_{k \in Y} SV_k \quad (3.9)$$

$$w_k = SV_k / T^2(SV) \quad (3.10)$$

where  $Y$  is any subset, which contains  $y$  elements, of scenario set  $Sn = \{1, 2, \dots, |Sn|\}$ ,  $T$  is the sum of  $y$  largest elements.

Note that all calculations are performed in Python by coding the required algorithms. So, calculations are made easily regardless of the number of factor levels and factors.

The model is formulated as:

Indices

$k, t$ : Index for scenarios (1, ...,  $K$ )

Parameters

$SV_k$ : The value of scenario  $k$

$D_{kt}$ : The distance between scenario  $k$  and  $t$

$w_k$ : Normalized value of the scenario  $k$

$\alpha$ : The weight of distance in the objective function

$\beta$ : The weight of scenario values in the objective function

$TV$ : Threshold value for scenario values

$MaxS$ : The maximum number of scenario to be selected

$MinD$ : The minimum distance between scenarios to be selected

$M$ : Big number

Decision Variables

$S_k$ :  $\begin{cases} 1 & \text{scenario } k \text{ is selected} \\ 0 & \text{o/w} \end{cases}$

$z_{kt}$ :  $\begin{cases} 1 & \text{if scenarios } k \text{ and } t \text{ are selected} \\ 0 & \text{o/w} \end{cases}$

$$Max \sum_k^{K-1} \sum_{t,t>k}^K z_{kt} (\alpha D_{kt} + \beta (w_k + w_t)) \quad (3.11)$$

$$S_k = 1 \quad k = argmax_{i=1,\dots,K} SV_i \quad (3.12)$$

$$\sum_{k=1}^K S_k \leq MaxS \quad (3.13)$$

$$TV - SV_k \leq M (1 - S_k) \quad \forall k \quad (3.14)$$

$$S_k + S_t - 1 \leq z_{kt} \quad \forall k, t \text{ ve } k < t \quad (3.15)$$

$$2 - S_k - S_t \leq M(1 - z_{kt}) \quad \forall k, t \text{ ve } k < t \quad (3.16)$$

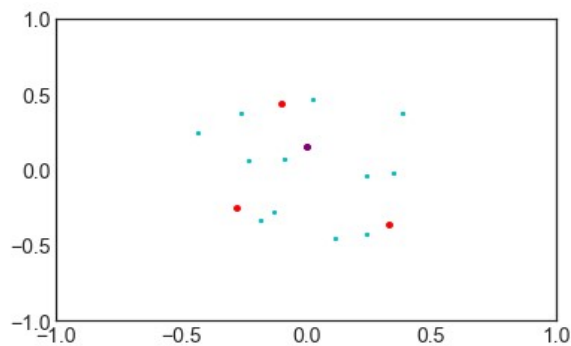
$$D_{kt} \geq MinD z_{kt} \quad \forall k, t \text{ ve } k < t \quad (3.17)$$

$$S_k, z_{kt} \in \{0,1\} \quad \forall k, t \text{ ve } k < t \quad (3.18)$$

Eq. 3.11 is the objective function which maximizes the weighted sum of distances and normalized scenario values. In the objective function, weights of distances and normalized scenario values can be determined using the parameters  $\alpha$  and  $\beta$ . Eq. 3.12 ensures that the scenario with the largest scenario value is selected. Eq. 3.13 limits the number of scenarios to be selected. Eq. 3.14 ensures that scenarios whose values are lower than the threshold value are not selected. Eq. 3.15 and Eq. 3.16 guarantee that only scenarios involved in the determined scenario set are considered in the objective function. Eq. 3.17 ensures that there are at least  $MinD$  differences between scenarios to be selected. Eq. 3.18 is a binary constraint.

When the mathematical model is solved by taking the threshold value for scenario values as 58, the maximum number of scenarios ( $MaxS$ ) as 4, the minimum distance between scenarios ( $MinD$ ) as 0.5,  $\alpha$  and  $\beta$  as 0.5, the selected scenarios are  $S_9 = [l_{11} \ l_{22} \ l_{31} \ l_{43}]$ ,  $S_{18} = [l_{11} \ l_{23} \ l_{32} \ l_{43}]$ ,  $S_{19} = [l_{12} \ l_{21} \ l_{31} \ l_{41}]$  and  $S_{33} = [l_{12} \ l_{23} \ l_{31} \ l_{43}]$ . The mathematical model can be solved under varying values of the parameters to obtain different solutions. These solutions can be examined by experts to choose the most suitable one.

**Step 6. Visualization of scenarios:** The scenarios, which have a greater scenario value than the threshold value, are visualized to observe how the selected scenarios and the others disperse in the future space and show the representativeness of the selected scenarios. This enhances the transparency of the method. Multidimensional scaling (MDS) is used via ‘Scikit-learn’ (Pedregosa et al., 2011) for mapping scenarios into a two-dimensional space using dissimilarities between scenarios. The scenarios are illustrated in Figure 3.4. The red ones represent the selected scenarios.



**Figure 3.4 :** Visualizations of scenarios.

### 3.3 Application

Warehouse systems are evolving due to recent technological developments to be operated in a more efficient and flexible way. The companies will have to improve and adapt their operations in a way that complies with the technologies in the next ten years. Although technologies like IoT, robots and RFID provide many advantages to them over accuracy and efficiency of operations, the new form of technology and transformation may lead to some risks and challenges like high investment costs, cybersecurity, skilled labor and economic instability. Hence, companies should foresee and analyze future changes to create competitive and sustainable practices. In this regard, the proposed approach was applied for a medium-sized manufacturing company to explore a final set of scenarios about future warehouses in 2030 in order to support their strategy development process.

Based on the literature review and experts' opinions, 10 factors with two or three levels were identified. The factors and their levels are shown in Table 3.7. Considering the factor levels, all the combinations constitute 3,456 scenarios. The scenario set becomes as follows:

$$S = \left\{ \begin{array}{l} S_1([l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}]), \\ S_2([l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}]), \dots, \\ S_{3456}([l_{13}, l_{22}, l_{32}, l_{42}, l_{52}, l_{62}, l_{73}, l_{82}, l_{92}, l_{10,3}]) \end{array} \right\}$$

To measure the quality of these scenarios, five criteria were determined. The determination of criteria varies depending on the type of the scenario process, purpose, and problem domain of the study. Different criteria are employed in normative and exploratory studies, as well as quantitative and qualitative approaches. In this study, criteria were determined considering its semi-quantitative and exploratory nature, as well as application area. The criteria are plausibility ( $x_1$ ), significance ( $x_2$ ), adaptability ( $x_3$ ), consistency ( $x_4$ ) and dissimilarity ( $x_5$ ). Individual factor levels were assessed with respect to plausibility, significance and adaptability.

**Table 3.7 : Factors and factor levels.**

<b>Factors</b>	<b>Factor Levels</b>
Skilled Labor Shortage ( $fc_1$ )	Increased ( $l_{11}$ ) Current state ( $l_{12}$ ) Decreased ( $l_{13}$ )
Availability of Technologies (i.e. advanced robotics, vision cameras, radio waves, magnets, or laser) ( $fc_2$ )	Widely improved and Sufficient ( $l_{21}$ ) Partly Improved ( $l_{22}$ )
Adoption of IoT ( $fc_3$ )	Low level ( $l_{31}$ ) High level ( $l_{32}$ )
Cybersecurity Risk ( $fc_4$ )	High ( $l_{41}$ ) Limited ( $l_{42}$ )
Initial Investment Cost ( $fc_5$ )	Increased ( $l_{51}$ ) Decreased ( $l_{52}$ )
Managing Effort ( $fc_6$ )	More (overcoming problems will be more time-consuming) ( $l_{61}$ ) Less (easy solution) ( $l_{62}$ )
Pace of Demand ( $fc_7$ )	Faster ( $l_{71}$ ) Current state ( $l_{72}$ ) Slower ( $l_{73}$ )
Attitudes toward Transition ( $fc_8$ )	Positive ( $l_{81}$ ) Negative ( $l_{82}$ )
Legal Issues ( $fc_9$ )	Developing more strict policies and procedures ( $l_{91}$ ) Current state ( $l_{92}$ )
Government Support ( $fc_{10}$ )	More financial support and incentives ( $l_{10,1}$ ) Current state ( $l_{10,2}$ ) Tightened ( $l_{10,3}$ )

Domain experts assessed criteria weights (on the scale 0-1) and factor levels (on the scale 0-100) with respect to plausibility, significance and adaptability. The first two criteria are assessed by experts who are academics and experts in manufacturing and supply chain, while the company's adaptability can only be assessed by an expert with more than 10 years of experience working in the company. Criteria were determined in accordance with scenario planning and the application area. Consistency, plausibility and dissimilarity are the most important criteria for quantitative assessments in scenario planning. Significance and adaptability are important for companies to determine strategic plans. The assessments are given in Table 3.8 and Table 3.9.

**Table 3.8 : Criteria weights.**

Criteria	Weights		
	Expert 1	Expert 2	Expert 3
Plausibility	0.45	0.40	0.45
Significance	0.40	0.40	0.30
Adaptability	0.35	0.30	0.25
Plausibility and Significance	0.75	0.80	0.75
Plausibility and Adaptability	0.60	0.65	0.70
Significance and Adaptability	0.50	0.60	0.55

The revised criteria weights are calculated using the quadratic model given in step III.b. The revised weights are  $\hat{\mu}_{\{x_1\}}^* = 0.417$ ,  $\hat{\mu}_{\{x_2\}}^* = 0.350$ ,  $\hat{\mu}_{\{x_3\}}^* = 0.283$ ,  $\hat{\mu}_{\{x_1, x_2\}}^* = 0.767$ ,  $\hat{\mu}_{\{x_2, x_3\}}^* = 0.550$ ,  $\hat{\mu}_{\{x_1, x_3\}}^* = 0.650$ , and  $\hat{\mu}_{\{x_1, x_2, x_3\}}^* = 1.05$ , where the set  $X = \{x_1, x_2, x_3\}$ . The aggregated values for factor levels ( $V_{l_{ij}}$ ) given in the last column of Table 3.9 were calculated using Eq. 3.6. Considering the assessments  $f_{l_{12}}(x_1) = 40$ ,  $f_{l_{12}}(x_2) = 35$ ,  $f_{l_{12}}(x_3) = 50$ , the calculations are clarified for the factor level  $l_{12}$  as follows:

$$V_{l_{12}} = f(x_2)\hat{\mu}_{\{x_1, x_2, x_3\}}^* + (f(x_1) - f(x_2))\hat{\mu}_{\{x_1, x_3\}}^* + (f(x_3) - f(x_1))\hat{\mu}_{\{x_3\}}^*$$

$$V_{l_{12}} = 35 \times 1 + (40 - 35) \times 0.65 + (50 - 40) \times 0.283 = 41.08$$

Consistency values between level pairs were assessed by each expert. The scenario values were calculated using Eq. 3.7 by utilizing the average consistency values. Due to involving a huge number of scenarios, namely 3,456, the entire data cannot be provided here. The calculations are demonstrated through  $S_1 = [l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}]$  as follows:

$$SV_1 = ((V_{l_{11}} + V_{l_{21}})c_{l_{11}l_{21}} + (V_{l_{11}} + V_{l_{31}})c_{l_{11}l_{31}} + (V_{l_{11}} + V_{l_{41}})c_{l_{11}l_{41}} \\ + (V_{l_{11}} + V_{l_{51}})c_{l_{11}l_{51}} + (V_{l_{11}} + V_{l_{61}})c_{l_{11}l_{61}} + \dots \\ + (V_{l_{81}} + V_{l_{10,1}})c_{l_{81}l_{10,1}} + (V_{l_{91}} + V_{l_{10,1}})c_{l_{91}l_{10,1}}) / 9 \\ = ((67.00 + 62.58) \times 0.4 + (67.00 + 60.75) \times 0.5 \\ + (67.00 + 72.01) \times 0.6 + (67.00 + 75.58) \times 0.5 \\ + (67.00 + 69.50) \times 0.9 + \dots + (49.76 + 58.26) \times 0.7 \\ + (60.00 + 58.26) \times 0.75) / 9 = 346.43$$

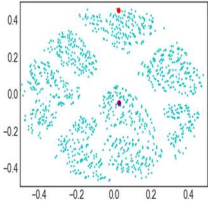
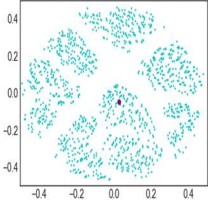
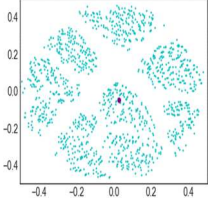
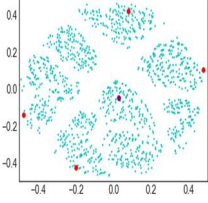
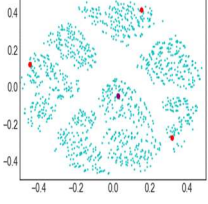
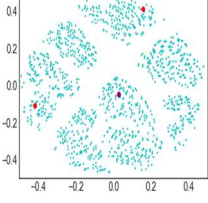
**Table 3.9 : Assessment values of the factor levels.**

Factor Level	Plausibility	Significance	Adaptability	Factor Level Value
Increased ( $l_{11}$ )	60	65	80	67.00
Current state ( $l_{12}$ )	40	35	50	41.08
Decreased ( $l_{13}$ )	30	70	40	46.00
Widely improved and Sufficient ( $l_{21}$ )	35	80	90	62.58
Partly Improved ( $l_{22}$ )	60	65	75	65.58
Low level ( $l_{31}$ )	50	75	60	60.75
High level ( $l_{32}$ )	40	60	70	53.83
High ( $l_{41}$ )	75	90	40	72.10
Limited ( $l_{42}$ )	40	50	45	44.50
Increased ( $l_{51}$ )	70	75	85	75.58
Decreased ( $l_{52}$ )	45	60	30	46.76
More (overcoming problems will be more time-consuming) ( $l_{61}$ )	65	75	70	69.50
Less (easy solution) ( $l_{62}$ )	50	55	30	47.09
Faster ( $l_{71}$ )	80	70	75	75.34
Current state ( $l_{72}$ )	70	60	45	60.68
Slower ( $l_{73}$ )	30	45	20	32.92
Positive ( $l_{81}$ )	55	60	25	49.76
Negative ( $l_{82}$ )	70	80	75	74.50
Developing more strict policies and procedures ( $l_{91}$ )	40	80	70	60.00
Current state ( $l_{92}$ )	50	40	35	43.01
More financial support and incentives ( $l_{10,1}$ )	60	75	30	58.26
Current state ( $l_{10,2}$ )	50	40	35	43.01
Tightened ( $l_{10,3}$ )	40	70	65	55.50

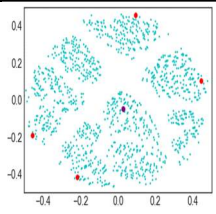
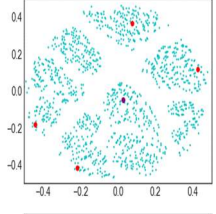
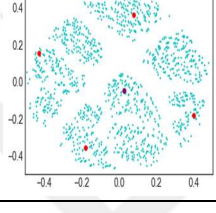
After the scenario values were obtained, the parameters of the mathematical model were determined. Distances between scenarios and normalized scenario values were calculated using Eq. 3.8 and Eq. 3.10. Nine different cases were constructed to select the best solution by adjusting the threshold value ( $TV$ ) and the minimum distance between scenarios ( $MinD$ ). These cases also simplify the selection of parameter values to get better results. Recall that the number of cases to solve the model was selected considering the trade-off between the effective parameter selection and the convenience of the solution performance – i.e. avoiding to create a time consuming model requiring an overburden. The maximum number of scenarios ( $MaxS$ ) was determined as 5,  $\alpha$  and  $\beta$  as 0.5 for all settings. The parameters and model solutions are given in Table 3.10. Visual representation of scenarios is also given in the first column (red circles represent the selected scenarios). The mathematical model was solved using Gurobi 9.5 with Python 3.8. Based on the settings, the problems are solved within different durations. For the parameter settings 337 (threshold) and 0.7

(minimum distance), the lowest number of potential scenarios and the shortest duration are obtained, while for the parameter settings 321 and 0.5, the highest number of potential scenarios and the longest duration are obtained (see Table 2.10). Examining the time data, it's evident that as the number of scenarios increases, the solution time also increases significantly. Therefore, the complexity can be considered to fall within the exponential time class.

**Table 3.10 :** Different cases for the mathematical model.

Setting No	Visualization of scenarios	Threshold value (TV)	Minimum distance (MinD)	Solution time (sec)	Objective function value	Total distance and # selected scenarios
1		321	0.7	0.03	0.85	0.7 (2)
2		329	0.7	0.01	0	0 (1)
3		337	0.7	0.01	0	0 (1)
4		321	0.6	17.76	7.85	6.6 (5)
5		329	0.6	0.07	4.66	3.7 (4)
6		337	0.6	0.04	2.34	1.8 (3)

**Table 3:10 (continued):** Different cases for the mathematical model.

Setting No	Visualization of scenarios	Threshold value (TV)	Minimum distance (MinD)	Solution time (sec)	Objective function value	Total distance and # selected scenarios
7		321	0.5	4000.2	7.81	6.6 (5)
8		329	0.5	1021.92	7.75	6.3 (5)
9		337	0.5	4.48	7.68	6 (5)

When the objective function value, the total distance between the selected scenarios ( $\sum_k \sum_t D_{kt} z_{kt}$ ) and visual representation of scenarios were taken into account, the best two solutions were Cases 4 and 7. For these cases, the graphs demonstrated that the selected scenarios satisfactorily cover the scenario space. While producing 6.6 total distance with 5 distinct scenarios, case 7 is suffering from a time limit. Since there is a trade-off between the solution time and solution quality, case 4 was selected as the best solution. It will be reasonable to select the threshold value between the median and third quartile and assign at least 0.5 to the minimum distance to ensure that at least half of the factor levels in scenarios are different. The selected scenarios are given in Table 3.11.

**Table 3.11 :** Selected scenarios.

Scenario No.	Scenario vectors
295	$[l_{11}, l_{21}, l_{32}, l_{41}, l_{51}, l_{61}, l_{71}, l_{82}, l_{91}, l_{10,1}]$
672	$[l_{11}, l_{22}, l_{31}, l_{41}, l_{52}, l_{61}, l_{72}, l_{82}, l_{92}, l_{10,3}]$
2087	$[l_{12}, l_{22}, l_{32}, l_{41}, l_{51}, l_{62}, l_{73}, l_{82}, l_{92}, l_{10,2}]$
2857	$[l_{13}, l_{21}, l_{32}, l_{42}, l_{52}, l_{62}, l_{72}, l_{81}, l_{91}, l_{10,1}]$
3027	$[l_{13}, l_{22}, l_{31}, l_{42}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,3}]$

Finally, scenario narratives are described based on the selected scenarios to assist organizations' strategic planning process. For the application, an example narrative based on the first scenario can be: "The warehouses will experience rapid

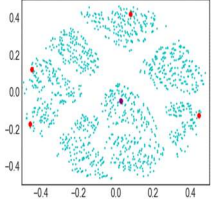
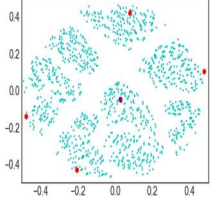
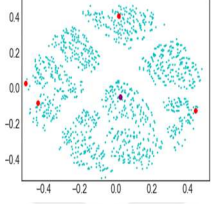
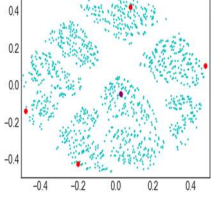
developments of technologies, also legal policies and incentives will support the industry for investments. At the same time, the industry will face some risks and challenges regarding investment costs, labors' competence and attitudes.". Accordingly, the company may formulate the following strategy "Implementing the transition process gradually to reduce the risks". It should be noted that these examples are provided for clarification purposes and the strategy planning process is beyond the scope of the proposed approach.

### 3.4 Sensitivity Analysis

The sensitivity analysis is implemented by altering the parameters  $\alpha$  and  $\beta$  in the mathematical model. Scenario planning experts may want to assign different weights for dissimilarity and normalized scenario values. For some experts, the dissimilarity may be more important than the scenario values or vice versa. Besides, some may want to use only dissimilarity or only scenario values. In this regard, four cases displayed in Table 3.12 are analyzed in the application.

In Table 3.12, when only dissimilarity ( $\alpha = 1$ ) is considered (Case 2), one of the maximum total distance ( $\sum_k \sum_t D_{kt} z_{kt}$ ) is obtained. However, the total scenario values ( $\sum_k \sum_t ((w_k + w_t) \times z_{kt})$ ) become the smallest in comparison to other cases. When only normalized scenario values ( $\beta = 1$ ) are considered, the maximum total weight is obtained along with the minimum total distance which results in selecting more similar scenarios compared to other cases. For a more balanced solution, both of them are used as in the first and fourth cases. The fourth case dominates the second case due to having equal total distance with higher scenario values. These four cases demonstrate that preferences regarding parameters may bring advantages or disadvantages at some points. The proposed model produced reliable and meaningful results. These results clearly illustrate that the significant changes observed in total distance and scenario values provide evidence on the impact of considering different weights.

**Table 3.12 :** Cases for different weights in the objective function.

Setting No	Visualization of scenarios	Parameters TV, MinD, MaxS	$\alpha$ , $\beta$	Solution time (sec)	Total distance and # selected scenarios	Total normalized scenario values
1		321 0.6 5	0.3 0.7	31.55	6.4 (5)	9.19
2		321 0.6 5	1 0	16.92	6.6 (5)	9.07
3		321 0.6 5	0 1	13.94	6.2 (5)	9.21
4		321 0.6 5	0.7 0.3	19.56	6.6 (5)	9.09

### 3.5 Comparative Analysis

In order to demonstrate the effectiveness of the proposed approach, it was compared with the existing methods in the literature. To ensure an unbiased and comprehensive comparison, alternative weighting, assessment and selection methods were employed using the same data. In this regard, three alternative approaches were specified. The first two approaches differ from the proposed one in that they employ alternative (subjective and objective) methods to weigh the criteria. Stepwise Weight Assessment Ratio Analysis Method (Chang, 2023) (SWARA) was used as the subjective weighting method, while Entropy (Singh, Singh, Ranakoti, & Kumar, 2023) method was used as the objective weighting method. Once the weights for the criteria were established, the same remaining stages of the proposed approach were applied using these determined weights.

In the third approach, the proposed approach is compared with the method proposed by Tietje (2005), which is one of the most widely used quantitative methods in scenario

planning. Tietje's method performs scenario assessment and selection based on consistency and distance criteria. The assessment is based only on the consistency criterion. It calculates the consistency value of the scenarios by using different indicators for the pairwise consistency of the factor levels in the scenario. A filtering process is performed by setting a threshold value for the scenario consistency values. Selection is also based on the distance criterion. In the comparison, the overall consistency of a scenario was calculated using the additive indicator and the procedure, “distance to selected”, was performed for the selection process.

In the mathematical model of the proposed approach, a threshold value was determined to eliminate scenarios based on their quartile values. This threshold for scenario values is chosen as the midpoint between the median and the third quartile value in all approaches. In Tietje's method, this value is used for scenario filtering. The methods and results used in the four alternative approaches together with the proposed approach are given in Table 3.13.

**Table 3.13 : Comparison of methods.**

Approaches compared	Weighting Method	Scenario Assessment Method	Scenario Selection Method	Total distance between selected scenario pairs	Objective Function Value	Selected Scenarios
1	SWARA	Proposed Approach	Proposed Approach	6.4	7.78	[295, 743, 2088, 2487, 3289]
2	Entropy	Proposed Approach	Proposed Approach	6.4	7.69	[295, 648, 2253, 2788, 3026]
3	-	Consistency based	Distance to selected	6.6	7.37	[959, 1476, 2005, 2357, 2773]
4	Proposed Approach (Choquet)	Proposed Approach	Proposed Approach	6.6	7.85	[295, 672, 2087, 2857, 3027]

According to total distance and objective function values, the proposed approach performed better than the approaches based on the weighting methods SWARA and Entropy. The proposed approach has allowed the selection of a more representative set of scenarios. Tietje's approach lacks a weighting method as it solely relies on consistency without incorporating an objective function value. Additionally, it doesn't employ any objective function value due to its iterative selection solely based on distance after the scenario filtering process. While both approaches yield the same total distance, the proposed method stands out for its selection based on four distinct criteria and distance, allowing for an exploration of different scenarios, and leading to more robust results.

Each selected scenario in an approach was compared to every scenario in other approaches based on distances. The minimum distance for each scenario was then chosen, and the total distances were obtained by summing these minimum distances (see Table 3.14). Approaches 1, 2, and 4 are closer to each other, as they account for multiple criteria, while approach 3 shows greater distance due to its focus on a single criterion and a different scenario selection method.

**Table 3.14 :** Distances between selected scenarios across approaches

<b>Approach</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
<b>1</b>	0	1.4	1.5	0.8
<b>2</b>	1.4	0	1.8	1
<b>3</b>	1.5	1.8	0	1.6
<b>4</b>	0.8	1	1.6	0

### **3.6 Discussion and Conclusion**

This study proposed a novel approach for the assessment and selection of future scenarios which support organizations in determining a future perspective and specifying strategies. The theoretical and practical implications as well as the limitations of the proposed approach are summarized below.

In the proposed approach, scenarios were evaluated based on combinations of factor levels as it is complex and impractical to evaluate scenarios directly. Factor levels were assessed with respect to multiple criteria considering individual and joint weights to improve the effectiveness and accuracy of the process. A new indicator has been proposed to derive Scenario Values by considering both factor level assessments and the consistency between factor level pairs. Thanks to the proposed assessment approach, scenarios, inherently qualitative, have been quantified for comparability. Since the combining factor levels yields too many scenarios to consider, a mathematical model was developed to select the most representative and effective scenarios. An application was presented for the assessment and selection of scenarios about future warehouses to support the development of strategies for the warehouse of a production company. The application along with a sensitivity analysis also allowed us to examine the applicability and effectiveness of the proposed approach. Also, a comparative analysis has provided evidence that supports the contributions of the proposed approach.

A quadratic model was proposed to determine the weights of the criteria according to the measure rules. It is generally very difficult to have experts directly evaluate the weights according to these rules. Therefore, the absence of any rules simplifies the assessment for experts and the proposed quadratic model updates these weights to satisfy the rules. Additionally, the aggregation of individual assessments into group judgments is also facilitated by this model. The overall values of the factor levels were calculated by using the Choquet integral considering the individual and joint criteria weights. The use of joint criteria weights was intended to obtain more accurate results. The findings of the comparative analysis, where different weighting methods (Choquet, SWARA, and Entropy) were compared, indicate better results for the proposed method. The proposed approach has revealed scenarios with higher representativeness and greater importance in terms of the criteria.

For scenario selection, an integer programming model with a flexible objective function based on distances and scenario values was proposed. The sensitivity analysis showed that the results differ according to the importance given to the distance or scenario values. Furthermore, different settings were proposed to determine parameters within the model, with two prominent settings emerging. While the total distance between scenarios remains the same (6.6), differences arise in objective function values (7.85 vs 7.81). Considering the trade-off between time and results, a practical approach was adopted to quickly arrive at a viable solution and select the final set of scenarios.

Compared to a well-known approach from the literature, proposed by Tietje, the proposed method yields similar results in terms of total scenario distances (6.6). However, considering multiple criteria has led to differentiation among selected scenarios. Consequently, it has obtained more representative scenarios with respect to different constraints and reduced information loss, which improved the comprehensiveness and accuracy of the scenario assessment and selection process.

From a managerial point of view, identifying potentially significant future scenarios allows organizations to proactively prepare and adapt to these circumstances. This enables them to generate strategies or test existing ones by identifying opportunities and threats. In the warehouse application, potential future scenarios were revealed. Based on these scenarios, necessary projects can be developed, and long-term strategies can be defined. As processes evolve, strategies can be tested and updated in

response to technological advancements, political shifts, and other factors. For example, it is important to think in advance about what to do in the scenario where regulations will be introduced and incentives will be provided, but at the same time costs will increase significantly and the skilled workforce will diminish. The company must evaluate decisions regarding investments in areas such as automation and workforce optimization, determining when to increase these investments based on different scenarios. In short, by developing strategies in the light of scenarios, organizations can reduce future uncertainties and increase their adaptability.

The proposed approach also involves some limitations. Consistency was considered only between level pairs because of the difficulty and complexity in assessing all subsets of the factor level set. Representing consistency among more than two factor levels also increases the number of assessments excessively for experts. If there is a manageable number of factors and levels, the higher order consistencies can be assessed by the experts. Otherwise, it may bring a burden that is beyond the cognitive capacity of human beings and also end up with a huge cost in terms of time and effort. To include higher order consistencies, a calculation method may be developed. Similarly, as the number of criteria increases (especially for more than five), the assessment process becomes very complex for experts. Alternative aggregation procedures or methods can be applied or developed to overcome this assessment burden.

The assessments in the approach are based on expert judgments. If the application area has enough sources to extract information, text mining may be used along with the expert assessments. Learning based approaches to determine higher order joint criteria weights can be derived. If there exist casual relationships between criteria, techniques like Multi Stepwise Weight Assessment Ratio Analysis (M-SWARA) can be utilized for weighting criteria.(Kou, Pamucar, et al., 2024) To address long computational times for some settings in the proposed mathematical model used to select scenarios, heuristic methods can be developed. Moreover, the mathematical model can be formulated and solved as a multi-objective model, when additional objectives need to be considered (Kou, Xiao, Cao, & Lee, 2021). Strategies or projects developed based on selected scenarios can be chosen using Quality Function Deployment (QFD)-based approaches (Kou, Dinçer, Yüksel, & Alotaibi, 2024). The approach may also be applied to different domains such as product or service development (Asan, Polat, &

Sanchez, 2008) where alternative combinations of components or processes are assessed.



#### **4. A SYSTEMATIC APPROACH TO THE ANALYSIS OF BARRIERS AND DRIVERS OF THE ESCO MARKET IN TURKEY<sup>3</sup>**

Energy efficiency has become one of the major concerns of many industries due to the overall climate change, economic developments, fluctuating prices of energy resources, technological innovations and increasing demand for renewable energy. The increasing awareness of sustainable development in recent years has promoted this growing interest. In this study, energy efficiency will be defined as “reducing the energy consumption without causing any decline in production quality and quantity in industrial establishments” (see (EIE, 2007)). By implementing energy efficiency activities, firms may avoid waste, increase their productivity, and decrease their costs and emission levels. These activities can be either outsourced or they can be performed inside the firm by investing to the necessary assets such as workforce, equipment, technology, etc. As a form of outsourcing, energy service contracting plays a critical role in realizing energy efficiency improvements (Steve Sorrell, 2007). These contracts, offered by energy service companies (ESCOs), provide an inclusive service package to the clients that enable firms to deal with various difficulties in planning, implementing and monitoring their energy efficiency projects. The type of contract mostly preferred by ESCOs suggests an energy savings offer to commercial and industrial customers in which payments are subject to the energy savings achieved or the renewable energy produced (Okay, Okay, Konukman, & Akman, 2008).

Although a trend of growth can be observed across many ESCO markets during the past few years (Bertoldi & Boza-Kiss, 2017), there are still certain factors hindering the development of the energy service industry. Especially, capital inadequacy of local firms, lack of effective risk management, transparency and disclosure problems of firms, risk-averse approach of the banking system, difficult to fulfill principles and procedures in the recent legal communiqué on ESCOs, and insufficient knowledge of

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<sup>3</sup> This chapter is based on the paper (A shorter version of this publication has been provided to avoid repetitive explanations) “Yanmaz, O., Kadaifci, C., Asan, U., & Bozdog, E. (2018). A Systematic Approach to the Analysis of Barriers and Drivers of the ESCO Market in Turkey. *Energy Management—Collective and Computational Intelligence with Theory and Applications*, 405-426. ”

end-users and firms are some of the typical barriers reported in the literature (Onaygil & Meylani, 2007; Okay et al., 2008; Akman, Okay, & Okay, 2013). Recently, a number of articles and reports have been published that identify and analyze key barriers and drivers for the development of the ESCO markets. Most of these studies rely on survey data collected by means of questionnaires (Kalangos, 2017; Bertoldi & Boza-Kiss, 2017; Kindström, Ottosson, & Thollander, 2017), in-depth interviews (Hannon, Foxon, & Gale, 2015; S. Sorrell et al., 2000) or Delphi studies (Pätäri & Sinkkonen, 2014). Providing either an overview of locally relevant factors or of factors within a specific sector (see Bertoldi & Boza-Kiss, 2017), the main concern of these studies is to group and prioritize these factors. However, they do not employ any further systematic analysis to closely examine the causalities and the relationships between the actors and barriers. Only few studies suggest a systematic approach to analyze the causal relationships between factors shaping the ESCO market. Fuzzy cognitive mapping (Asan, Kutlu, & Kadaifci, 2011), fuzzy time cognitive mapping (C. Kadaifci, Kucukyazici, Asan, & Bozdog, 2014) and DEMATEL (Basak, Asan, & Kadaifci, 2012) are methods employed for this purpose. These studies also ignore the roles played by the main actors of the market.

In order to address the issues mentioned above, this chapter suggests a systematic approach that allows a detailed analysis of the barriers, drivers and actors of the energy service contracting market. It does not only examine the barriers and their direct causal relationships but also reveals important indirect relationships which may change the priorities of the barriers. The proposed approach provides also an overview of the interplay between the actors. Examining the actors' plans, motivations and the balance of power among them allows a better understanding of the strategic issues of the energy service contracting market. To justify the effectiveness and applicability of the proposed approach, a case is provided where the energy service contracting market in Turkey is examined. In the recent past years the energy industry in Turkey has undergone a change in terms of restructuring and deregulation. The high growth rate of Turkey's annual energy demand, the high dependence on imports to meet the current demand, the high energy intensity of the economy and the geopolitical position of Turkey indicate the need of further energy-efficiency investments and also the necessity of planning, implementing and controlling these investments (Turkyilmaz, 2016). Experts who have knowledge and experience on energy service contracting

were involved in the process of determining the barriers, drivers, actors and their relationships. The findings provided the basis for developing strategies for the energy service contracting market in Turkey.

The rest of this chapter is organized as follows. In order to familiarize the reader with structural analysis and actors' behavior analysis, the theoretical foundations of the proposed approach are summarized in Section 2. In the following section the proposed approach and its stages are presented. In order to demonstrate the applicability and effectiveness of the proposed approach an application to the ESCO Market in TURKEY is provided Section 4. Finally, the contributions and limitations of the proposed approach are summarized.

#### **4.1 Theoretical Basis of the Proposed Approach**

Scenarios are not intended to predict the future, instead they are stories for anticipating it (Saritas & Aylene, 2010) and are used when several interdependent external and internal factors need to be considered and especially the future is somewhat uncertain (Godet, 1994). It seems unrealistic to predict a single future while dealing with numerous interdependent factors, which the decision makers may or may not have control on them, and the uncertainty about the future. Thus, scenario methodologies are developed to consider all possible futures, to explore alternative ways to reach them, and to show possible consequences (Godet, 1994). Among different scenario methodologies, the one belongs to the "la prospective" school, is proposed by Michel Godet in order to i) detect the priority issues, namely key variables, ii) determine the relationships between these variables and the main actors related to the system under study, and how powerful these actors to bring their projects into reality, and finally iii) describe the system in form of scenarios under some specific assumptions (Godet, 1994).

In this study, the first two steps of the aforementioned scenario methodology, which are two separate qualitative approaches, respectively called as structural analysis and MACTOR (*Matrix of Alliances and Conflicts: Tactics, Objectives and Recommendations*), are used. Structural analysis allows to detect the priority issues, in other words the key variables related to the scenario field, and MACTOR provides a strategic point of view by exploring actor-variable relationships and the power of these actors. In the following part, the theoretical basis of these approaches are given.

After determining the key variables or scenarios, the actors and their objectives related to the system need to be identified. Key variables provide a manageable scenario building process by dealing with a few critical factors, namely the most influential, dependent, and key factors, instead of all of them, but they constitute only one single dimension of the process. The actors in the system have different objectives either compatible or incompatible with the system's overall objectives and they may take several actions to reach their own goals. Thus, the moves of actors, their actions, and the balance of power need to be examined (Godet, 1994). Examining the relationships between the actors as well as their role and power on the specific topics concerning the subject and on each other provide a significant information to build more realistic and reliable scenarios.

The MACTOR method, developed in 1985, is based on a structural analysis which identifies actors and key strategic issues (Heger, Monath, & Kind, 2010), relationships between actors, potential alliances and conflicts, and also the balance of power (Munteanu & Apetroae, 2007). As pointed out by the developer of the MACTOR method, Michel Godet, "In order to identify the most probable results, it is necessary to fully understand the actors' projects and intentions, their methods of action on one another, coupled with the constraints imposed on them" (Godet, 1982). The MACTOR method produces either a graphical representation which can also be identified as a positioning map of actors based on their influence and dependence values or the convergence and divergence matrices and maps. The distances between actors show the potential alliances and conflicts by demonstrating how convergent or divergent they are. Besides observing the relative strength through convergence and divergence matrices and maps, the actors can be classified based on their position on the positioning map as dominant, dominated, independent, and key actors (Munteanu & Apetroae, 2007).

This qualitative scenario methodology consisting of two distinct and also sequential methods provides scenario analysts a useful approach to deal with interrelations among numerous factors and also among considerably high number of actors. Even they are proposed as scenario tools, each can be separately or successively used in many areas and for different managerial problems. In the scope of this study, both structural analysis and MACTOR are used and a new approach to energy efficiency studies is proposed in terms of ESCOs.

## 4.2 Proposed Approach

The proposed approach consists of two methods of scenario methodology: structural analysis and MACTOR. Determining key variables in the selected area provides a more compact and manageable scenario building process, while determining particular actions corresponds to these key variables and key actors have a significant power on taking these actions and examining the relationships between them result in more coherent and reliable scenarios. Instead of identifying the drivers directly based on the scenario field analysis, literature review, and/or expert opinions, determining them by considering the key variables improves relevance of the process of thought through the right questions asked to the actors (Godet, 1994). This approach aims to provide a new systematic way to recommend macro level strategies to the leading actors who have a significant impact on the actions determined.

Based on the key barriers determined in structural analysis, the drivers correspond to these variables and the actors have a considerable role in the system are identified and relationships between them are analyzed to reveal the importance of drivers and also the actual roles of actors on them to take strategic actions to deal with existing barriers. In this study, the policies to be followed in ESCO market to overcome existing barriers are selected as drivers, and from this point on, the term driver is used to refer to the policies. The MACTOR method consists in the following steps (Godet, 1994):

- 1. Identifying Drivers Correspond to the Key Variables:** The drivers correspond to the determined key variables are identified and described. These drivers represent strategic issues on which the actors confront each other, or in other words on which the actor have convergent or divergent objectives.
- 2. Identifying Actors Related to the Problem on Hand:** The key actors having a direct or indirect control over the determined drivers are identified.
- 3. Assessing Actor-Driver Relationships:** In order to run the MACTOR method, there are two main inputs collected in two matrices. The first matrix is the position matrix (MAO) that gives the position of actors over issues. The second matrix (MDA) gives the direct relationships between actors. The matrix is used to obtain agreement and disagreement coefficients, in other words convergence and divergence of actors to the particular drivers.

The actor-driver matrix is prepared in order to examine the relationship between the actors and the drivers. A group of experts assess these relationships by using a predetermined scale where 0 indicates being neutral, +1 indicates being in favor of and -1 indicates being opposed to a particular driver.

**4. Building Direct and Indirect Relationship Matrices:** To associate the impacts of actors on drivers to the power of actors and to obtain the weighted actor-driver matrix, the relationships between actors are examined. The direct relationships between actors are assessed by a group of experts and by using matrix multiplication, the indirect relationships are obtained. Note that only the second degree paths are checked, so the square of the actor-actor matrix is calculated.

The actor-driver matrix and actor-actor matrix are merged by using a power coefficient. Actors' balance of power, a scalar determining the relative strength of each actor, is used in order to provide reasonable strategic recommendations. Power coefficient for each actor is calculated by using Eq. 4.1 based on the values in the indirect relationship matrix. If the scalar is high, the actor is in a stronger position. Then, the balance of power coefficients is calculated by using Eq. 4.2 to facilitate understanding and calculation.

$$r_i = \frac{M_i}{\sum M_i} \times \frac{M_i}{M_i + D_i} \quad (4.1)$$

$$r_i^* = \frac{r_i}{\bar{r}_i} \quad (4.2)$$

where  $M_i$  is the total direct and indirect influence value of actor  $i$ ,  $D_i$  is the total direct and indirect dependence value of actor  $i$ ,  $r_i$  is the power coefficient of actor  $i$  and  $r_i^*$  is the balance of power coefficient of actor  $i$ .

**5. Calculating the Weighted Matrix:** The weighted matrix is obtained by multiplying the rows of actor-driver matrix by corresponding power coefficient to show the convergence and divergence that reflect the strength of the actors.

**6. Calculating Matrices and the Graphs of Convergence and Divergence:** The convergence and divergence matrices are calculated by using the weighted matrix. To obtain the convergence (or divergence) values of each actor pair on a particular policy, the values associated with these two actors are compared. If these actors have the same position towards any policy (i.e. the sign of the assessment is same), the absolute sum of the relevant assessments are calculated and then it is divided by two. This absolute

arithmetic average demonstrates the common approach of these actors to the relevant policy. The average has a positive sign to represent the convergence and a negative sign to represent the divergence values. The convergence and divergence maps are prepared by using the values in these matrices separately where actors are represented by nodes connected by arcs, the thickness of which is proportionate to the intensity of the convergence (or divergence) between pairs of actors (Bendahan, Camponovo, & Pigneur, 2004).

### **4.3 Application**

#### **4.3.1 The ESCO market in Turkey**

During the last decade, the energy industry in Turkey has been greatly affected by the deregulation and restructuring activities. The global competitiveness has become very critical and to become a powerful player in this competitive environment, Turkey has to make difference with its technological innovations, effective and efficient energy activities, production and service quality (C. Kadaifci et al., 2014).

According to the report of International Energy Agency in 2005, ESCOs were not yet operating in the Turkish market, however energy efficiency activities have actually been being performed since 1995 in different sectors such as pharmaceuticals, chemicals, automotive, agriculture, paint, food and beverages, airport, hospital, and building by several medium-scale energy companies (Akman et al., 2013). In Turkey, ESCOs (which are known as Energy Efficiency Consulting Companies) operate as consulting firms which are state authorized and obliged to obey the Energy Efficiency Law (EEL) and its communiqué, which primarily aims to increase competitive advantage of Turkey in the global market (Akman et al., 2013). Although the EEL has been developed in 2007 as a result of adapting with the European Union accession period, the communiqué of the EEL related to ESCOs was released in 2012. During the development process of this communiqué, ESCO licenses have been suspended by the Ministry of Energy and Natural Resources (MENR) and candidate companies had to wait until the regulations are approved (Akman et al., 2013). Today, MENR, Energy Efficiency Coordination Board (EECB) and General Directorate of Renewable Energy (GDRE) are responsible for energy efficiency activities. The EEL promotes the efficient use of energy and covers administrative structuring, energy auditing, financial instruments and incentives, awareness raising and the establishment of an ESCO

market for energy efficiency services. With the EEL it is aimed to end the state monopoly and allow private-sector participation in energy industries, aiming at cost-effective pricing through competition (Okay et al., 2008).

A strategic plan for energy efficiency covering the years 2012-2023 have been developed by General Directorate of Renewable Energy (EIE, 2012). According to this plan, the decrease in the amount of energy consumed per GDP of Turkey in the year 2023 is targeted as 20%. The strategies reported in this plan, which are critical for the energy service contracting market, can be summarized as follows i) to reduce energy intensity and energy losses in industry and services sectors, ii) to decrease energy demand and carbon emissions of the buildings; to promote sustainable environment friendly buildings using renewable energy sources, iii) to provide market transformation of energy efficient products, iv) to increase efficiency in production, transmission and distribution of electricity, to decrease energy losses and harmful environment emissions, v) to reduce unit fossil fuel consumption of motorized vehicles, to increase share of public transportation in highway, sea road and railroad and to prevent unnecessary fuel consumption in urban transportation, vi) to use energy effectively and efficiently in public sector, and vii) to strengthen institutional capacities and collaborations, to increase use of state of the art technology and awareness activities, to develop financial mechanisms except public financial institutions (see EIE, 2012). These strategies can only be achieved in collaboration with ESCOs.

In the literature, there are a number of informative studies about the ESCO market in Turkey which helped us identifying the potential barriers and drivers influencing the market's development. Onaygil and Meylani (2007) give an overview of energy service contracting and ESCOs and provide policy suggestions for the forthcoming Turkish ESCO market. Okay et al. (2008) present views with regard to the funding and related risks that are likely to be associated with the forthcoming Turkish ESCO market. Also, the current situation of the Turkish ESCO market is analyzed through the latest communiqué by Akman et al. (2013) from the 2013 perspective by considering the present barriers and opportunities. In another recent study, Kalangos (Kalangos, 2017) investigates the barriers and policy drivers to energy efficiency (EE) in specific sectors in Turkey (automotive, chemicals and textile industries). Results point to the need for a policy structure that tackles the recorded poor behavioral and

managerial practices on energy efficiency (EE), the lack of private EE capital funds, the inadequate energy service companies' marketplace and energy suppliers' loose EE practices. Besides, there are studies focusing on the analysis of barriers and/or success factors of energy performance contracting projects in different countries (Bertoldi & Boza-Kiss, 2017; Kindström et al., 2017).

#### **4.3.2 Steps of the proposed approach**

The proposed approach is applied to the ESCO market in Turkey. Effective use of energy resources is a non-negligible issue for Turkey when it comes to increasing energy consumption, climate change, and trade balance deficit. While energy efficiency has such a great significance, awareness created and precautions taken about this issue are quite a little. For a good future to live, it is inevitable to take potential energy efficiency actions and give this topic the credit it deserves.

In this study, barriers that hinder development of ESCO market being important factor on energy efficiency are analyzed using structural analysis. Then necessary actions to overcome these barriers and actors playing a significant role to take these actions are analyzed using MACTOR method.

Key barriers determined to be based on structural analysis are listed below (Please refer to the publication for a detailed explanation of how the key barriers were determined).

- D1: Economic market barriers
- D3: Poor market incentives
- D4: Lack of customer awareness and understanding
- D6: Lack of customer information
- D7: Lack of trust by the clients in ESCOs
- D8: Lack of well-established partnerships between ESCOs and subcontractors
- D9: Negative influence of failed projects on the market
- D11: Organizational and behavioral barriers
- D14: Taxation rules that discourage investment

Improvement of ESCO market depends on overcoming these key barriers obtained by using structural analysis. In order to deal with these hindering factors, some significant actions are needed to be taken. Not only the actions but also the key actors who are responsible for or have impact on these actions are crucial in terms of the future progress of the ESCO market. The actor-related part of the proposed approach produces positioning map of actors, the conflicts and potential strategic alliances among them, and consequently the strategic actions recommended to the practitioners.

### ***Identifying Policies and Actors***

Policies to overcome key barriers and actors having direct or indirect effects on these barriers are identified. Here, the main questions are who are the actors in ESCO market, how many actors should be taken into account, and which policies are considered correspond to the key barriers determined in the previous methodology. Since the purpose of this study is to propose a new systematic approach for recommending macro level strategies in general to any market, but in particular to the ESCO market in Turkey, the leading actors who have a significant impact on the policies are selected. Besides, the policies are identified based on a detailed literature survey including the academic articles and industry reports, and also on the opinions of experts in the related area.

Policies cover six issues including increasing financial incentives (O1), enabling regulations about the market such as energy price, project development processes, etc. (O2), aligning strategies and priorities of ESCOs with the market (O3), providing information and awareness for customers (O4), establishing national policies and legislations to improve the sector (O5), forming documentation of market analysis and sectoral memory (O6). Eight actors which are Governments/Ministries (A1), Local Authorities (i.e. Municipalities) (A2), Energy Efficiency Coordination Board (covers TÜBİTAK, TMMOB, etc.) (A3), European Union (A4), ESCOs (A5), Technology Suppliers (A6), Customers/End Users (A7), and Organizations Providing Financial Support (A8) are identified based on their role in the ESCO market.

### ***Assessing Actor-Policy Relationships***

Two types of relationships including actor-policy and actor-actor are assessed by the same group of experts formed to assess the interrelationships among barriers. First, the actor-policy relationships are assessed by using a predetermined scale where +1

indicates being in favor of a particular policy, -1 indicates being opposed to that policy, and 0 means being neutral. In contrast to the previous methodology, the average assessments of experts are used for the further analysis. In Table 4.1, the overall assessments are shown.

**Table 4.1 :** The overall assessments of expert w.r.t the actors' position towards policies

	O1	O2	O3	O4	O5	O6
A1	-1	-1	0	1	1	-1
A2	0	0	0	1	0	0
A3	1	1	0	1	1	1
A4	1	1	0	1	1	1
A5	0	1	1	1	1	-1
A6	0	0	-1	0	0	0
A7	0	0	-1	0	0	0
A8	-1	0	0	0	0	1

### ***Building Direct and Indirect Relationship Matrices***

While it is difficult to make actors talk about their strategies and priorities, and ask them to reveal their own purposes as well as their strengths and weaknesses, it is considerably easy to direct them to talk about other actors in the system (Godet, 1994). Thus, after identifying their divergence and convergence to the particular policies, examining their relationships with others and seeking for their power on others will show the whole picture.

Actor-actor direct relationship matrix is filled based on the influence of one actor on another by using a scale from 0 to 3 (0: No, 1: Weak, 2: Average, and 3: Strong influence). The overall assessments of experts related to the actor-actor relationships is given in Table 4.2.

**Table 4.2 :** Overall assessments on actor-actor relationships

	A1	A2	A3	A4	A5	A6	A7	A8
A1	0	2.33	2.33	1.00	2.67	1.83	1.33	1.83
A2	0.83	0	0.50	0.17	1.17	0.33	1.00	0.50
A3	1.67	1.33	0	0.17	1.67	0.17	0.50	0.33
A4	1.83	0.50	1.33	0	1.83	0.67	0.00	0.83
A5	1.33	0.83	1.17	0.33	0	1.83	2.83	1.17
A6	0.50	0.17	0.33	0.33	2.33	0	0.50	0.50
A7	0.17	0.50	0.17	0.17	2.83	0.33	0	0.33
A8	0.67	0.00	0.17	0.17	2.67	1.33	0.67	0

Similar to the CIA, indirect relationships are examined through matrix multiplications. At this point, only the second degree paths are checked whether there is an indirect influence of a particular actor on others. This matrix, given in Table 4.3, shows overall dependence and influence values.

**Table 4.3 : Indirect Relationships Between Actors**

	A1	A2	A3	A4	A5	A6	A7	A8	I
A1	0.00	6.81	6.75	2.81	21.39	9.61	13.19	7.25	67.81
A2	3.36	0.00	3.89	1.67	8.31	4.86	5.17	3.69	30.94
A3	4.03	5.64	0.00	2.64	9.00	7.28	8.58	6.06	43.22
A4	5.97	7.69	7.03	0.00	11.47	8.22	9.69	6.53	56.61
A5	5.42	6.56	5.25	2.94	0.00	5.64	4.89	5.39	36.08
A6	4.83	3.97	4.58	1.53	5.44	0.00	7.94	4.28	32.58
A7	5.17	3.11	4.33	1.39	3.28	6.25	0.00	4.22	27.75
A8	4.92	4.64	5.44	2.14	7.36	6.47	9.19	0.00	40.17
D	33.69	38.42	37.28	15.11	66.25	48.33	58.67	37.42	

**Constructing the Weighted Matrix**

In order to provide reasonable strategic recommendations, actors’ power coefficients are calculated and by using these, the balance of power coefficients is obtained to represent actors’ relative strength. The calculated coefficients are given in Table 4.4. According to the findings, while Government/Ministries (A1) has the strongest position of power, Customer/End Users appears to be in the weakest position in ESCO market.

**Table 4.4 : Balance of Power Coefficients**

Actors	r*
A1	1.99
A2	0.61
A3	1.02
A4	1.96
A5	0.56
A6	0.58
A7	0.39
A8	0.91

The balance of power coefficients and actor-policy matrix are used to construct weighted matrix. The weighted actor-policy matrix, given in Table 4.5, is obtained by multiplying each row of actor-policy matrix by power coefficient of the related actor corresponds to that row.

**Table 4.5 : The weighted actor-policy matrix**

	<b>O1</b>	<b>O2</b>	<b>O3</b>	<b>O4</b>	<b>O5</b>	<b>O6</b>
<b>A1</b>	-1,99	-1,99	0,00	1,99	1,99	-1,99
<b>A2</b>	0,00	0,00	0,00	0,61	0,00	0,00
<b>A3</b>	1,02	1,02	0,00	1,02	1,02	1,02
<b>A4</b>	1,96	1,96	0,00	1,96	1,96	1,96
<b>A5</b>	0,00	0,56	0,56	0,56	0,56	-0,56
<b>A6</b>	0,00	0,00	-0,58	0,00	0,00	0,00
<b>A7</b>	0,00	0,00	-0,39	0,00	0,00	0,00
<b>A8</b>	-0,91	0,00	0,00	0,00	0,00	0,91

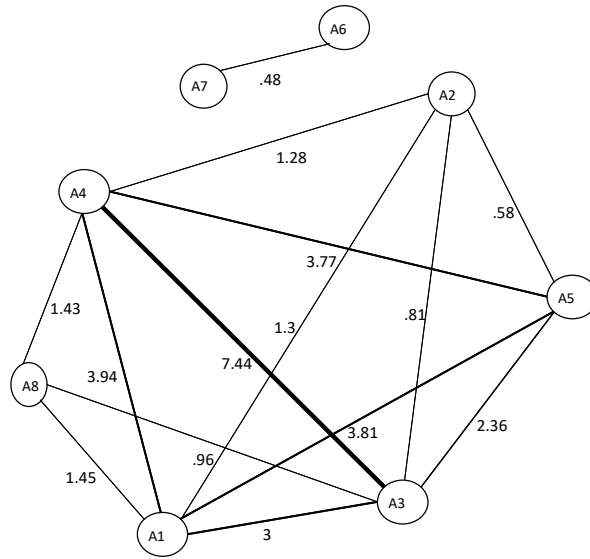
### *Calculating Matrices and the Graphs of Convergence and Divergence*

Two types of output are obtained as a result of MACTOR method: convergence and divergence matrices and maps. While convergence matrix identifies actors which have common positions over policies, divergence matrix identifies actors which have conflicts over them. Convergence and divergence maps in Figure 4.1 and 4.2 are prepared by using these matrices to show the position of actors on a map. The more the actors are distant one to another, the more the intensity of their convergence (or divergence) is important. The thickness of the lines between actors indicates how powerful the alliance or the conflict between the actors are.

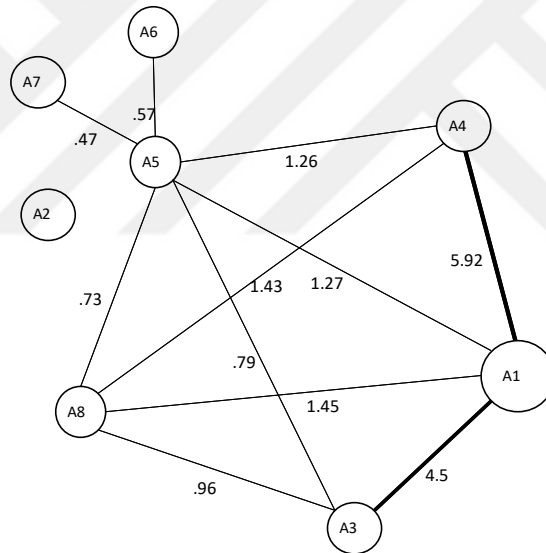
Convergence map shows that the Energy Efficiency Coordination Board and European Union have strong relationship and they are carrying out similar works about policies determined. Government/Ministries and ESCOs have common objectives. There are some allies and conflicts between Government/Ministries, Energy Efficiency Coordination Board, and European Union. Government/Ministries have common policies either with the Energy Efficiency Coordination Board and European Union. On the other hand, divergence map shows Government/Ministries strongly conflicts on some policies with these actors being allies. This shows coherent works are not carried out among these actors. Local Authorities, Technology Suppliers, Customers/End Users, and Organizations providing Financial Supports have not considerable common benefits with the other actors. Local Authorities, Technology Suppliers, ESCOs, and Customers/End Users have negligible conflicts on drivers with the other actors.

**Table 4.6 :** The Convergence and Divergence Matrices

	<b>A1</b>	<b>A2</b>	<b>A3</b>	<b>A4</b>	<b>A5</b>	<b>A6</b>	<b>A7</b>	<b>A8</b>
<b>A1</b>	0,00 0,00	1,30 0,00	3,00 -4,50	3,94 -5,92	3,81 -1,27	0,00 0,00	0,00 0,00	1,45 -1,45
<b>A2</b>	1,30 0,00	0,00 0,00	0,81 0,00	1,28 0,00	0,58 0,00	0,00 0,00	0,00 0,00	0,00 0,00
<b>A3</b>	3,00 -4,50	0,81 0,00	0,00 0,00	7,44 0,00	2,36 -0,79	0,00 0,00	0,00 0,00	0,96 -0,96
<b>A4</b>	3,94 -5,92	1,28 0,00	7,44 0,00	0,00 0,00	3,77 -1,26	0,00 0,00	0,00 0,00	1,43 -1,43
<b>A5</b>	3,81 -1,27	0,58 0,00	2,36 -0,79	3,77 -1,26	0,00 0,00	0,00 -0,57	0,00 -0,47	0,00 -0,73
<b>A6</b>	0,00 0,00	0,00 0,00	0,00 0,00	0,00 0,00	0,00 -0,57	0,00 0,00	0,48 0,00	0,00 0,00
<b>A7</b>	0,00 0,00	0,00 0,00	0,00 0,00	0,00 0,00	0,00 -0,47	0,48 0,00	0,00 0,00	0,00 0,00
<b>A8</b>	1,45 -1,45	0,00 0,00	0,96 -0,96	1,43 -1,43	0,00 -0,73	0,00 0,00	0,00 0,00	0,00 0,00



**Figure 4.1 : The convergence map**



**Figure 4.2 : The divergence map**

The 2023 strategies associated with policies developed to improve ESCO market are demonstrated in Table 4.7. In order to accomplish these strategies, required actions need to be taken for corresponding policies.

**Table 4.7 : Strategies-policies**

<b>2023 Strategies</b>	<b>Policies</b>
SP-01: To reduce energy intensity and energy losses in industry and services sectors	P2
SP-02: To decrease energy demand and carbon emissions of the buildings; to promote sustainable environment friendly buildings using renewable energy sources	P2-P5
SP-03: To provide market transformation of energy efficient products	P2-P5-P3
SP-04: To increase efficiency in production, transmission and distribution of electricity, to decrease energy losses and harmful environment emissions	P2
SP-05: To reduce unit fossil fuel consumption of motorized vehicles, to increase share of public transportation in highway, sea road and railroad and to prevent unnecessary fuel consumption in urban transportation	P2-P4-P5
SP-06: To use energy effectively and efficiently in public sector	P2-P5
SP-07: To strengthen institutional capacities and collaborations, to increase use of state of the art technology and awareness activities, to develop financial mechanisms except public financial institutions.	P1-P2-P3-P4-P6

All dominant actors have common understanding of and support for P4 and P5. Thus, these policies are likely to be realized. However, a considerable difference appears when it comes to the policies P1, P2, and P6. All 2023 strategies are related to P2 on which Government/Ministries have conflicts with the European Union and Energy Efficiency Coordination Board. Unless these three actors ensure coordination on this policy, realization of the following strategies seems rather challenging. Governments/Ministries and Organizations providing financial support have different opinions with European Union and Energy Efficiency Coordination Board with respect to P1 associated with the strategy SP-07. These actors should settle the conflict to accomplish SP-07. Even it creates an additional workload to maintain systematic documentation, analysis and control of the ongoing activities, Government/Ministries and ESCOs should try to reach a common ground with other actors to provide a better understanding and awareness as well as sectoral improvement.

#### **4.4 Conclusion**

This chapter suggests a new approach to the analysis of the potential barriers and drivers of energy service contracting markets. It allows to closely examine causalities by analyzing both direct and indirect relationships between the barriers as well as the actors and policies. Since the proposed approach considers the actors' plans, motivations and the balance of power among them, it provides the basis of a better understanding of the strategic issues of the energy service contracting market. The effectiveness and applicability of the proposed approach is demonstrated by a case study where the energy service contracting market in Turkey is

examined. The findings of the case study, verified by experts, point out the presence of potential conflicts among the actors and the risk of failure in realizing some critical policies in the future. Since the barriers and policies may vary depending on country specific factors such as managerial cultures, market structures and political-legal systems, it is difficult to generalize the empirical findings of the present study. A possible future research direction might be extending the proposed approach to consider also the uncertainty involved in the judgments.





## 5. CONCLUSIONS AND RECOMMENDATIONS

Scenario planning is a strategic tool for dealing with the complexities and uncertainties of the future. In today's highly competitive world, where rapid and dramatic changes are the norm, anticipating and responding to future adjustments is vital to organizational survival and success. Scenario planning provides a methodological framework for overcoming experts' cognitive constraints, allowing for a more complete analysis of possible alternative futures while promoting decision-making under risk and uncertainty. Furthermore, it provides companies with the foresight to identify and address both opportunities and threats, ensuring that they are better prepared to adapt to a changing environment. As a result, the adoption of systematic and comprehensive techniques for scenario planning is critical for efficiently managing uncertainty and assessing complexity.

Within the scope of the thesis, important problems in the scenario planning approach were addressed. To be more specific, scenarios, along with the factors and factor levels that constitute them, are qualitative concepts. To make a selection of a limited and small number among a huge number of scenarios, it is essential to quantify these concepts. In the methodological studies, to quantify and obtain high quality scenarios, the first three criteria were utilized to evaluate factor levels which constitute scenarios, which the future developments in multiple perspectives. Also, considering the interactions between the criteria in the aggregation process led to more realistic and dependable outcomes. A new indicator has been proposed to derive quantitative scenario values by considering both factor level assessments and the consistency between factor level pairs. To address the combinatorial problem of scenario selection, linear with a single objective and non-linear with multiple objective mathematical models were developed. By defining constraints and objectives to ensure the selection of diverse and high-quality scenarios that comprehensively represent future possibilities, the model supports the identification of scenarios that best prepare for future uncertainties. As a result of the models, four scenarios for urban mobility system were selected in the first methodological approach, while five scenarios for warehouse system were selected in the second methodological approach.

Some limitations of the first methodological study were addressed in the second methodological study. In the first study, interactions between criteria were assumed to be only positive by taking into account the measure rules. In the second study, a quadratic model was developed to take into account both positive and negative interactions, and the individual and joint weights of the criteria were optimized in accordance with the measure rules. In addition, while in the first study, a non-linear model considering only distance in the scenario selection model was proposed, in the second study, a linear model with an objective function considering scenario values and distance together was developed. Thus, both better quality scenario selection in terms of criteria and the selection of different scenarios that can cover the future are ensured. The linear model was also chosen to achieve faster solutions in applications with high complexity.

To demonstrate the effectiveness of the proposed approaches, a comparative analysis was conducted with existing methods from the literature. This allowed us to analyze both the impact of using criteria interactions and the effectiveness of the method. As a result, the proposed methods yielded better results in selecting high-quality and diverse scenarios in terms of criteria.

From a managerial point of view, identifying potentially significant future scenarios allows organizations to proactively prepare and adapt to these circumstances, which enables them to generate several objectives to pursue. However, achieving these objectives requires consideration of the plans, motivations, and power dynamics of relevant actors. To address this, MACTOR method was performed to analyze relationships between objectives with respect to selected scenarios and actors. This analysis identified allied actors with shared objectives, with whom strategies were developed to achieve these goals. Thus, a structured framework was provided to guide the progression from selected scenarios to the formulation of effective strategies.

The proposed approaches have certain limitations that could be addressed. If data extraction is feasible within the study area, evaluations could be streamlined by incorporating text mining techniques alongside expert assessments. To reduce complexity in the methodological approaches, only the consistencies of factor-level pairs were considered. An automated method could be developed to calculate higher-level consistencies based on these pairwise consistencies. Scenario selection is a combinatorial problem that becomes computationally expensive as problem

complexity increases. To address this, heuristic algorithms could be developed to solve the mathematical model used for scenario selection, enabling faster solutions for large-scale problems with numerous factors and levels. For the MACTOR, the uncertainty involved in the judgments could also be considered.

The approaches proposed in these studies are not limited to scenario planning problems, they can also be applied to decision-making problems involving systems composed of discrete components. Product development is one such example, where the methodologies can be applied. Products consist of many different parts, each with several characteristics. Using the analogy between products and scenarios, the proposed methodologies can be effectively applied to similar problems in other areas.





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## CURRICULUM VITAE

**Name Surname** : Özgür YANMAZ

### **EDUCATION** :

- **B.Sc.** : 2013, Izmir University of Economics, Faculty of Engineering and Computer Science, Department of Industrial Engineering (Full Scholarship)
- **M.Sc.** : 2017, Istanbul Technical University, Faculty of Management, Department of Industrial Engineering

### **PROFESSIONAL EXPERIENCE AND REWARDS:**

2016 - 2024 Research Assistant, Department of Industrial Engineering at Istanbul Technical University, Istanbul, Turkey

2021 - 2022 Visiting Researcher at Valencia Polytechnic University, INGENIO (CSIC-UPV), Valencia, Spain

### **JOURNAL ARTICLES:**

- **Yanmaz, O., & Asan, U. (2024).** A novel approach to scenario assessment and selection. *International Journal of Information Technology & Decision Making* (Accepted by Reviewers, Awaiting for Editor's Decision)
- **Yanmaz, O., & Asan, U. (2024).** A novel scenario planning approach considering criteria interaction in multi-criteria evaluation: An application to urban mobility. *Decision Science Letters*, 13(2), 461-470.
- **Kadaifci, C., Yanmaz, O., & Altug, G. (2023).** A systematic approach to examine the attitudes of actors towards objectives: a case study of football industry in Turkey. *Middle East Journal of Management*, 10(6), 592-618.
- **Yanmaz, O., & Kabak, Ö. (2023).** A two phase approach based on multi-objective programming and simulation for physician scheduling in emergency rooms. *International Journal of Applied Decision Sciences*, 17(1), 36-59.
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#### CONFERENCE PROCEEDINGS:

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- **Bozdog, E., Yanmaz, O., & Kadaifçi, C.** (2019). A hesitant fuzzy correspondence analysis. In *International Conference on Intelligent and Fuzzy Systems* (pp. 362-368). Cham: Springer International Publishing.
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- **Yanmaz, O., & Kabak, Ö.** (2017, July). Physician scheduling problem in an emergency department of a public hospital. *24th International Conference on Multiple Criteria Decision Making (MCDM 2017)*, Ottawa, Canada.

#### BOOK CHAPTERS:

- **Yanmaz, Ö., Kadaifçi, C., Asan, U., & Bozdog, E.** (2018). A Systematic Approach to the Analysis of Barriers and Drivers of the ESCO Market in Turkey. *Energy Management—Collective and Computational Intelligence with Theory and Applications*, 405-426.