INCORPORATING COMPLEXITY INTO RISK MANAGEMENT: AN INTEGRATED RISK ASSESSMENT PROCESS FOR MEGA CONSTRUCTION PROJECTS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

H. HÜSEYİN EROL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
CIVIL ENGINEERING

NOVEMBER 2020

Approval of the thesis:

INCORPORATING COMPLEXITY INTO RISK MANAGEMENT: AN INTEGRATED RISK ASSESSMENT PROCESS FOR MEGA CONSTRUCTION PROJECTS

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ABSTRACT

INCORPORATING COMPLEXITY INTO RISK MANAGEMENT: AN INTEGRATED RISK ASSESSMENT PROCESS FOR MEGA CONSTRUCTION PROJECTS

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November 2020, 217 pages

Complexity and risk are inherent components of mega construction projects due to their unique characteristics. However, existing project management practices fail to incorporate complexity-based thinking into risk management. The lack of integration between complexity and other risk-related concepts leads to unrealistic risk assessments, ineffective management strategies, and poor project performance, which decrease the belief in risk management as a value-adding process in projects. In order to fill this gap, this research aims to unveil the relationship between complexity and risk in mega construction projects and propose a holistic approach that can help to manage the project risk and complexity. For this purpose, a mixed-methods research approach was adopted to analyze the data acquired through interviews with 18 participants from 11 mega construction projects carried out by the Turkish contractors. While the quantitative analysis uncovered the relationship between complexity and risk in numerical terms, the qualitative analysis provided further evidence about the nature of this relationship by exposing their links. By combining the findings of both analyses, the Integrated Risk Assessment Process (IRAP), which includes the concepts of risk, uncertainty, complexity, and management strategies, was proposed. Then, IRAP was operationalized by linking these concepts via an Analytic Network Process (ANP) model. The weights of the parameters in the ANP model were determined by a two-round Delphi study conducted with the domain experts. The data obtained using an interactive data collection tool in the first round were consolidated through an expert panel in the second round. Following the finalization of the model, validation studies were conducted to test both the risk quantification performance of the ANP model by comparing the results with the findings from 11 mega construction projects and the applicability of IRAP in practice with a demonstrative case study. The results revealed the potential of IRAP and the ANP-based quantitative model in terms of managing and monitoring the risks in mega construction projects. Therefore, the proposed risk assessment approach is expected to contribute both to the literature by explaining the links between risk, uncertainty, complexity, and management strategies and to the practitioners by supporting risk-informed decision-making process in mega construction projects. Although IRAP has been developed considering the dynamics of mega construction projects, it can also be implemented in other project-based industries to incorporate complexity into the risk management process.

Keywords: Mega Construction Projects, Complexity, Risk, Uncertainty, Management Strategies

ÖZ

KARMAŞIKLIĞIN RİSK YÖNETİMİNE DAHİL EDİLMESİ: MEGA İNŞAAT PROJELERİ İÇİN BİR ENTEGRE RİSK DEĞERLENDİRME SÜRECİ

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Kasım 2020, 217 sayfa

Karmaşıklık ve risk, benzersiz özellikleri nedeniyle mega inşaat projelerinin doğal bileşenleridir. Bununla birlikte, mevcut proje yönetimi uygulamaları karmaşıklık temelli düşünceyi risk yönetimine dahil etmekte başarısız olmaktadırlar. Karmaşıklık ve riskle ilgili diğer kavramlar arasındaki entegrasyon eksikliği, gerçekçi olmayan risk değerlendirmelerine, etkisiz yönetim stratejilerine ve kötü proje performansına yol açarak, projelerde değer yaratan bir süreç olarak risk yönetimine olan inancı azaltmaktadır. Bu boşluğu doldurmak amacıyla, bu araştırma mega inşaat projelerinde karmaşıklık ve risk arasındaki ilişkiyi ortaya çıkarmayı ve proje riskini ve karmaşıklığını yönetmeye yardımcı olabilecek bütüncül bir yaklaşım önermeyi amaçlamaktadır. Bu amaçla, Türk müteahhitleri tarafından gerçekleştirilen 11 mega inşaat projesinden 18 katılımcıyla yapılan mülakatlardan elde edilen verileri analiz etmek için karma yöntemler araştırma yaklaşımı benimsenmiştir. Nicel analiz karmaşıklık ve risk arasındaki ilişkiyi sayısal olarak ortaya koyarken, nitel analiz aralarındaki bağlantılarını açığa çıkararak bu ilişkinin doğası hakkında daha fazla delil sağlamıştır. Her iki analizin bulguları birleştirilerek, risk, belirsizlik, karmaşıklık ve yönetim stratejileri kavramlarını içeren Entegre Risk Değerlendirme

Süreci (IRAP) önerilmiştir. Daha sonra, bu kavramlar bir Analitik Ağ Süreci (ANP) modeli aracılığıyla birbirine bağlanarak IRAP işlevsel hale getirilmiştir. ANP modelindeki parametrelerin ağırlıkları, alan uzmanlarıyla yapılan iki turlu bir Delphi çalışmasıyla belirlenmiştir. İlk turda interaktif bir veri toplama aracı kullanılarak elde edilen veriler, ikinci turda bir uzman paneli aracılığıyla konsolide edilmiştir. Modelin kesinleştirilmesinin ardından, hem sonuçları 11 mega inşaat projesinden elde edilen bulgularla karşılaştırarak ANP modelinin risk ölçüm performansını hem de örnek bir vaka çalışması ile IRAP için pratikte uygulanabilirliği test etmek için doğrulama çalışmaları yapılmıştır. Sonuçlar, mega inşaat projelerindeki risklerin yönetilmesi ve izlenmesi açısından IRAP ve ANP tabanlı sayısal modelin potansiyelini ortaya koymuştur. Bu nedenle, önerilen risk değerlendirme yaklaşımının hem risk, belirsizlik, karmaşıklık ve yönetim stratejileri arasındaki bağlantıları açıklayarak literatüre hem de mega inşaat projelerinde riske dayalı karar verme sürecini destekleyerek uygulayıcılara katkı sağlaması beklenmektedir. IRAP, mega inşaat projelerinin dinamikleri göz önünde bulundurularak geliştirilmiş olsa da karmaşıklığı risk yönetimi sürecine dahil etmek için diğer proje bazlı endüstrilerde de uygulanabilir.

Anahtar Kelimeler: Mega İnşaat Projeleri, Karmaşıklık, Risk, Belirsizlik, Yönetim Stratejileri

Dedicated to dear Bilgenur…

ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisors Prof. Dr. İrem Dikmen Toker and Prof. Dr. M. Talat Birgönül for their invaluable contributions to this thesis. They supported, encouraged, and guided me patiently throughout my research. I am also grateful to Assist. Prof. Dr. Güzide Atasoy Özcan for her suggestions and feedback during all stages of this research. Moreover, I would like to thank the members of my thesis examining committee for their constructive comments.

This research was funded by a grant from the Scientific and Technological Research Council of Turkey (TÜBİTAK), Grant No. 217M471. TÜBİTAK's support is gratefully acknowledged.

I would like to thank my friends Görkem Eken, Gizem Bilgin, Uğurcan Ertaymaz, and Hazal Deniz Kaya for their efforts and contributions in this long-termed research project. I am also grateful to the companies collaborating to share their data and anonymous participants who took their precious time to contribute to this research.

Words cannot express how thankful I am to my wife Bilgenur for her endless love, support, encouragement, patience, and friendship. She always motivated me to dream of a better future. This thesis would not have been possible without all the sacrifices she has made. I feel privileged to share my life with such a special person.

I am sincerely thankful to my parents Güler Erol and Ruhi Enver Erol, who devoted their lives to me. I owe all of my success to their priceless sacrifices. I am also very thankful to my dear sister Anıl Erol Tunçay and my brother-in-law Ferhat Tunçay. They helped me in every possible way to get through the difficult times. The support of my mother-in-law Asuman Keskin and my brother-in-law Alper Keskin was always precious. I am also grateful to my late father-in-law Ali Keskin for having created such a beautiful family. I would also like to thank all other family members, especially my grandfather Resul Öztürk, my dear aunts Memnune Öztürk and Nevin Öztürk, and my cousin Ahmet Öztürk for their moral support to complete my thesis.

I would like to give special thanks to G-Team members Sıla Gülgeç and Murat Yeğin for their sincere friendship and all the good memories we have shared over the years. I am also thankful to my dear friends Alper Çam, Mert Aker, Ömer Baykal, Onur Alican Kurtar, Burak Dündar, Erman Güngör, Mert Bilir, Beste Özyurt, Başak Seyisoğlu, and Pınar Bilgin.

I would like to express my thanks to Dr. Gözde Bilgin, Dr. Saman Aminbakhsh, and Dr. Abroon Qazi for all the academic and non-academic help they provided. During my years as a research assistant at METU, it was always fun to work with the good people of Room-407. I would also like to thank my colleagues at Hacettepe University for their support.

Finally, I would like to take this opportunity to express my deepest gratitude to our eternal leader Mustafa Kemal Atatürk for everything he has done for us.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
AHP	Analytic Hierarchy Process
ALOE	Attributes, Links, Objects, and Events
ANN	Artificial Neural Network
ANP	Analytic Network Process
AoN	Activity-on-Node
APE	Absolute Percentage Error
BBN	Bayesian Belief Network
BIM	Building Information Modelling
CEPC	Complexity and Emergent Property Congruence
CPS	Cyber-Physical Systems
DB	Design-Build
GDP	Gross Domestic Product
HoPC	House of Project Complexity
IPMA	International Project Management Association
IRAP	Integrated Risk Assessment Process
IT	Information Technology
MAPE	Mean Absolute Percentage Error
PMBOK	Project Management Body of Knowledge
PMI	Project Management Institute

PMOMIM	Program Management Organization Maturity Integrated Model
PPP	Public-Private Partnership
PRAM	Project Risk Analysis and Management
ProCRiM	Project Complexity and Risk Management
RAMP	Risk Analysis and Management for Projects
RFID	Radio-Frequency Identification
RSPE	Risk Score Prediction Error
SD	System Dynamics
SEM	Structural Equation Modelling
SoS	System of Systems
TOE	Technical, Organizational, and Environmental

CHAPTER 1

INTRODUCTION

This chapter presents introductory information about the research context. The first section explains the motivation for undertaking this research by discussing the current role of complexity in risk management approaches. Then, based on the identified research gap, research questions are raised in the next section. The subsequent section presents the research objectives by outlining the methodology utilized to answer research questions. The last section describes the organization of the thesis.

1.1 Motivation of the Research

Risk management, as one of the 10 knowledge areas in the Project Management Body of Knowledge (PMBOK) Guide, is a process of identifying, analyzing, responding, and monitoring events or conditions that have an effect on project objectives (Project Management Institute [PMI], 2017). In terms of contributions to their performance objectives, risk management has particular importance for construction projects characterized by large capital investments, long durations, a multitude of resources, a high number of stakeholders, volatile environments, and a high level of complexity (Cagliano, Grimaldi, & Rafele, 2015). Therefore, analyzing the risks that stem from these characteristics is a critical task in the management of construction projects, especially large-scale ones (Chapman, 2016; Sanchez-Cazorla, Alfalla-Luque, & Irimia-Dieguez, 2016).

In this respect, a variety of risk analysis methods, including “coarse risk analysis,” “job safety analysis,” “failure modes and effects analysis,” “hazard and operability studies,” “structured what-if technique,” “fault tree analysis,” “event tree analysis,” “Bayesian networks,” and “Monte Carlo simulation” can be utilized by the practitioners to assess the risks in their projects (Aven, 2015). Depending on their maturity level, project management organizations can analyze the risks at different stages of the projects with more sophisticated analysis techniques as well (del Caño & de la Cruz, 2002). Furthermore, standards like ISO 31000 (International Organization for Standardization [ISO], 2018) and various guidelines, such as Project Risk Analysis and Management (PRAM) (Association for Project Management [APM], 2010) and Risk Analysis and Management for Projects (RAMP) (Institution of Civil Engineers [ICE], 2014), provide structured approaches for project risk management.

Even though the risk is a widely discussed topic in the literature and several knowledge artifacts exist about managing risks in projects, the construction industry does not have a good reputation in terms of risk management practices (Taroun, 2014). Risk management is usually perceived as a “tick-the-box exercise” rather than a value creation process (Willumsen, Oehmen, Stingl, & Geraldi, 2019). Thus, risk management practices are not frequently employed in the daily routine of even large and complex projects (de Carvalho & Rabechini Junior, 2015).

The deficiency in the risk management practices of construction projects can be explained by reasons such as “difficulty interpreting results,” “lack of organizational support,” “lack of policy and procedures,” and “lack of technical expertise” (Senesi, Javernick-Will, & Molenaar, 2015). In addition to these explanations, several researchers pointed out the disintegrated risk management approach as one of the bottlenecks in practice (Haimes, 2018; Kardes, Ozturk, Cavusgil, & Cavusgil, 2013). Poor conceptualization of risk-related factors, such as complexity and uncertainty, may result in inadequate risk models and plans and, consequently, decrease the belief in risk management as a value-adding process (Dikmen, Budayan, Birgonul, & Hayat, 2018). Thomé, Scavarda, Scavarda, and Thomé (2016) particularly noted that treating complexity and risk from distinct perspectives may result in poor risk management applications.

Despite its relevance to the risk, complexity is a term that is not well understood in the construction industry (Dikmen, Qazi, Erol, & Birgonul, 2020). In terms of project management perspective, complexity is related to the properties of the project that make to perceive, predict, and control its overall behavior more difficult (Vidal & Marle, 2008). Properties like "large-scale," "sophisticated technology," "long duration," "large numbers of project participants and stakeholders," "globally dispersed locations of project execution," "high levels of uncertainty," and "high schedule and cost pressures in competitive and volatile economic environments" are some key reasons for ever-increasing complexity in construction projects (Ahn, Shokri, Lee, Haas, & Haas, 2017). Nonetheless, efforts aimed at treating these complexity characteristics within a structured risk management framework is limited.

The aforementioned methods, standards, and guidelines have made significant contributions to the body of knowledge by shedding light on how to handle uncertainty within the context of project risk management. However, although project complexity is mentioned as an issue to consider in risk management, these approaches usually fail to explain how complexity factors can be integrated into risk models and plans. For this reason, traditional approaches are often criticized for not being effective under high complexity (Cicmil, Williams, Thomas, & Hodgson, 2006; Haimes, 2018; Thamhain, 2013). Despite the existence of studies that offer insights into the link between complexity and risk (Afzal, Yunfei, Nazir, & Bhatti, 2019; Jensen & Aven, 2018; Thomé et al., 2016), the knowledge sources in construction project management literature fall short of explaining the role of project complexity in risk management. Disintegrated risk management approaches may be one of the reasons why many large-scale construction projects underperform (Dimitriou, Ward, & Wright, 2013). Moreover, they may reduce the confidence of practitioners, who have to deal with high levels of complexity in their projects, in the benefits of risk management (Botchkarev & Finnigan, 2015). Therefore, there is a strong need for developing new approaches that can incorporate complexity-based thinking into risk management to fill this research gap. This need constitutes the main motivation of the research.

1.2 Research Questions

The disconnection described in the previous section between complexity and risk management may be caused by ambiguity in the causality relations among risk-related concepts. Current perspectives in the literature usually conceptualize the relationships between complexity and other risk-related concepts with cause-effect frameworks (Padalkar & Gopinath, 2016). However, there may be intricate patterns between complexity and risk, which need to be unfolded through research efforts beyond simplistic explanations based on cause-effect relationships.

Unveiling their relationship is particularly important for megaprojects, which are not only exposed to more and greater risks but also known to be complex initiatives mainly due to their size, technological novelty, and the high number of stakeholders involved (Boateng, Chen, & Ogunlana, 2015; Hu, Chan, Le, & Jin, 2015b). The success of a megaproject depends considerably on how well complexity and risk are addressed during the decision-making (Dimitriou et al., 2013; Giezen, 2013; Kardes et al., 2013).

Investigating the integration of complexity into risk management may help to formulate appropriate management strategies for the megaprojects. Therefore, the aim of this research is to untangle the relationship between complexity and risk-related concepts in mega construction projects so that a holistic approach can be proposed to manage them. In this respect, the following four research questions are raised:

- **Research Question 1:** What kind of relationship exists between complexity and risk factors in mega construction projects?

- **Research Question 2:** What are the implications of this relationship in terms of developing an integrated risk management approach for mega construction projects?
- **Research Question 3:** How can the risks of mega construction projects be quantified based on the integrated risk management approach?
- **Research Question 4:** How can the integrated risk management approach be utilized in practice for managing risk-related factors of mega construction projects?

1.3 Research Objectives

In order to address the research questions presented in the previous section, the research objectives are set as follows:

- The first objective is to explore the relationship between complexity and risk in mega construction projects. For this purpose, a mixed-methods research approach was utilized to analyze quantitative and qualitative data gathered through interviews with 18 participants from 11 mega construction projects.
- The second objective is to propose an integrated risk management approach for mega construction projects. In this direction, a conceptual model was introduced as a consequence of the findings from mixed-methods research.
- The third objective is to build an analytical model to quantify the risks of mega construction projects based on the conceptual model. With the goal of addressing this objective, an Analytic Network Process (ANP) model was developed. The weights of the components in the ANP model were assigned by a two-round Delphi study conducted with five experts.
- The fourth objective is to validate the proposed approach with real applications. In this respect, validation studies were conducted to test both the risk quantification performance using the data of 11 mega construction projects and the applicability with a demonstrative case study.

1.4 Organization of the Thesis

The details of the research are provided in the forthcoming chapters. Accordingly, "Chapter 2" reviews the existing literature on project complexity and megaprojects to establish the research context. "Chapter 3" explains the three phases of the research methodology applied with respect to the research objectives introduced in the previous section. "Chapter 4" reports the findings from the first phase to propose a conceptual model. "Chapter 5" presents the details of the analytical model developed from the studies in the second phase. "Chapter 6" reports the results of the testing and validation studies in the third phase. Finally, "Chapter 7" concludes the research by summarizing the findings as well as presenting the contributions, the limitations, and the recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

Since the aim of this study is developing a complexity-based risk management approach for mega construction projects, "complexity" and "megaprojects" constitute the two main themes of the research scope. In this respect, the following two sections present a comprehensive review of the literature on these topics by considering their relevance to the concept of risk as well. Then, the third section discusses their shortcomings to emphasize the requirement for further research.

2.1 Complexity from the Project Management Perspective

The emergence of complexity science dates back to the studies that started at Santa Fe Institute in the 1980s (Jaafari, 2003). For more than three decades, researchers have been developing complexity-related theories, such as "complexity theory," "co-evolutionary theory," "organisational theory," "contingency theory," "theory of constraints," "systems theory," "network theory," "nonlinearity and chaos theory," and "adaptive self-organisation theory" (Bakhshi, Ireland, & Gorod, 2016). Due to ever-increasing complexity in projects, complexity research has also gained popularity among project management scholars who have been trying to describe, measure, and manage it since the 1990s (Geraldi, 2009). In this direction, the subsequent sections present prior studies that treated the complexity from the project management perspective.

The review starts with various definitions used to explain project complexity. Then, studies aimed to conceptualize the complexity are investigated. Following the discussion of frameworks that categorized the complexity factors, studies related to the quantification of the complexity are compiled in the next section. Since managing complexity has become one of the central issues in modern project management, studies devoted to this topic are addressed in the next section. Finally, the relationship between complexity and risk-related concepts is discussed to emphasize the need for their synthesis.

2.1.1 Definition of Complexity

There exist different approaches in the literature to define complexity. From the system perspective, complexity is associated with the difficulty in understanding, describing, or controlling not only the functioning of the system but also its dynamic behavior (Kiridena & Sense, 2016). Such systems are often called as complex System of Systems (SoS). According to Haimes (2018), a complex SoS is composed of several "interdependent and interconnected" systems that have intrinsic characteristics. The SoS perspective may be valid for the projects as well. Nowadays, many construction projects can be considered as complex systems that include various "processes," "activities," "players," "resources," and "information," which are dependent on each other (Zhu & Mostafavi, 2017). The existence of interwoven structures makes the behavior of these systems unpredictable. Understanding the individual components is usually not enough to comprehend the overall functioning of the complex systems. Moreover, the fact that projects are socially constructed entities increases the dynamic behavior further. For this reason, Whitty and Maylor (2009) described projects as "complex adaptive systems." There are also some approaches in the project management literature that explain the complexity by means of specific properties. For example, Bakhshi et al. (2016) listed the "ambiguity and uncertainty," "interdependency," "non-linearity," "unique local conditions," "autonomy," "emergent behaviors," and "unfixed boundaries" as the defining characteristics of the complex projects.

As complexity has been described in many different ways, there is not a standard definition of project complexity adopted by the majority of researchers (Ahn et al., 2017; Dao, Kermanshachi, Shane, Anderson, & Hare, 2017; Nguyen, Nguyen, Le-

Hoai, & Dang, 2015). Some of the most frequently used project complexity definitions in the project management literature are compiled in Table 2.1.

Table 2.1. Definitions of Project Complexity

Definition	Reference Study
". . . 'consisting of many varied interrelated parts' and can be operationalized in terms of differentiation and interdependency" (p. 202).	Baccarini (1996)
". . . the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system" (p. 1101).	Vidal and Marle (2008)
". . . an intricate arrangement of the varied interrelated parts in which the elements can change and evolve constantly with an effect on the project objectives" (p. 1203).	Bakhshi et al. (2016)
". . . the degree of interrelatedness between project attributes and interfaces, and their consequential impact on predictability and functionality" (p. 04016126-4).	Dao et al. (2017)

Although there are similarities between the definitions in Table 2.1, the way Vidal and Marle (2008) described the complexity is believed to suit best the project management perspective. For this reason, this definition was utilized in the later stages of the study.

2.1.2 Conceptualization of Complexity

In terms of conceptualization of complexity, the study of Baccarini (1996) was one of the initial attempts in the project management domain. Baccarini described "organizational" and "technological" dimensions as the main components of project complexity. While "organizational complexity" is related to the abundance of organizational units and interactions among them, "technological complexity" stems from the number of diversified project tasks and their interdependencies (Baccarini, 1996). Williams (1999) combined "organizational" and "technological" dimensions defined by Baccarini (1996) under the "structural complexity" term. "Structural complexity" pertains to the "number of elements" and "interdependence of elements." Besides the "structural complexity," Williams considered "uncertainty" as another dimension of project complexity and defined "uncertainty in goals" and "uncertainty in methods" as the sub-dimensions. Later on, Geraldi, Maylor, and Williams (2011) extended the complexity model of Williams (1999) by adding the dimensions of "dynamic," "pace," and "socio-political." "Dynamic complexity" refers to the change in project elements, such as specifications, goals, actors, and environmental components. "Pace complexity" pertains to the time pressure originated from urgency and criticality of the schedule goals. "Socio-political complexity," on the other hand, is related to the presence of both the emotional aspects related to the behavior of the stakeholders and political aspects related to the importance of the project (Geraldi et al., 2011). The model of Williams (1999) provided a basis for other studies as well. For instance, considering the perception of project managers, Dunović, Radujković, and Škreb (2014) added the "constraints" as the third dimension of the model. They asserted that "constraints of the environment," "constraints of resources," and "constraints of objectives" are the factors increasing the complexity. More recently, Maylor and Turner (2017) simplified the previous complexity model of Geraldi et al. (2011) by not only incorporating the "pace complexity" into the "structural complexity," but also synthesizing the "uncertainty" and "dynamic complexity" as the "emergent complexity." As a result, the initial conceptualization of Baccarini (1996) evolved into different models with the efforts of many project management scholars.

There are also some other approaches to conceptualize the complexity. For example, Vidal and Marle (2008) developed the Attributes, Links, Objects, and Events (ALOE) model to explain the sources of complexity in projects. According to the ALOE model, complexity is caused by the attributes of the project, objects that constitute the project system, and links between them, as well as occurred and potential project events. With a different approach based on the SoS view, Botchkarev and Finnigan (2015) identified complexity attributes in "product (service, result)," "project – internal environment," and "external environment."

On the other hand, some studies conceptualized the complexity, along with its impact on the project. In this respect, Lessard, Sakhrani, and Miller (2014) developed the House of Project Complexity (HoPC) model using a house metaphor. In the HoPC model, “inherent features” placed at the foundation of the house represent the fundamental features that contribute to project complexity. The layer “architectural constructs & arrangements” is related to the technical and institutional concepts that can be actively shaped. Finally, “emergent properties” at the roof of the house reflect the outcomes of the choices made during the process of project architecting. Thus, the HoPC model links the project performance and risk emergence with the inherent complexity features and actions taken to manage them. In a similar vein, the Complexity and Emergent Property Congruence (CEPC) framework proposed by Zhu and Mostafavi (2017) tackled the impact of complexity on project performance in terms of the capacity of the project system to cope with complexity. According to the CEPC framework, project complexity is composed of “detail complexity” related to the high number of variables and “dynamic complexity” associated with unclear and inconsistent relationships between the project components. The way these complexity dimensions affect the performance depends on the different types of capacities that a project system can possess. While “absorptive capacity” is related to being prepared against the negative impact of the complexity, “adaptive capacity” refers to being flexible to avoid them. On the other hand, in case of negative impact is realized, “restorative capacity” indicates the resilience of a project system to recover from the disruptions. Consequently, these studies suggest that a conceptual model containing management actions might reflect the effects of complexity on the project more accurately. Other studies related to the management of project complexity will be summarized in Section 2.1.5.

2.1.3 Complexity Frameworks

In addition to the models that conceptualize the complexity, frameworks towards the identification of the complexity factors have gained popularity since the 2010s.

These frameworks usually cluster the complexity factors under a few categories. While some studies determined the complexity factors by detailed literature analyses, some studies used experimental methods. As an example of the first approach, Bakhshi et al. (2016) classified 127 project complexity factors under "context," "belonging," "autonomy," "connectivity," "emergence," "diversity," and "size" themes through a comprehensive review of 423 papers published between 1990 and 2015. Based on the second approach, Dao et al. (2017) analyzed the survey data collected from 44 projects to identify 34 significant complexity indicators that separate high-complexity projects from low-complexity projects. The Technical, Organizational, and Environmental (TOE) framework, developed by Bosch-Rekveldt, Jongkind, Mooi, Bakker, and Verbraeck (2011) by combining these two approaches, is one of the most widely known studies in the project management domain. The framework contains 15 "technical," 21 "organizational," and 14 "environmental" complexity factors identified for large engineering projects. As the TOE framework provides a comprehensive list, it has been employed in many studies related to the project complexity (Bosch-Rekveldt, Bakker, & Hertogh, 2018; Floricel, Michela, & Piperca, 2016; Peñaloza, Saurin, & Formoso, 2020; Qazi, Quigley, Dickson, & Kirytopoulos, 2016). Therefore, it was utilized as the reference framework of this study in the later stages.

There are also some studies that used the conceptual model of Baccarini (1996) to build new complexity frameworks. For instance, Vidal and Marle (2008) identified 21 "technological" and 47 "organizational" complexity factors with the categories of "project system size," "project system variety," "interdependencies within the project system," and "element of context." Later, Qureshi and Kang (2015) employed Structural Equation Modelling (SEM) to statistically analyze the relationships between four categories determined by Vidal and Marle (2008). Based on this analysis, they identified the 16 most influential factors that belong to the "organizational complexity" category only.

On the other hand, some studies categorized the complexity factors considering their impact on project success. In this respect, Luo, He, Xie, Yang, and Wu (2017) determined the impact of 41 complexity factors under the “information,” “task,” “technological,” “organizational,” “environmental,” and “goal” clusters on the project success by correlation and factor analyses of 245 questionnaires. According to Montequín, Villanueva Balsera, Fernández, and Fernández (2018), complexity is directly associated with project failure. Based on this view, they classified 26 complexity factors that may cause failure under “organization,” “project,” “project manager and team members,” and “external environment” categories.

In some studies, the purpose of developing a complexity framework was to measure the project complexity over the factors in the framework. Such frameworks are covered together with the quantification of complexity in the next section.

2.1.4 Quantification of Complexity

Project management literature contains a variety of studies related to the quantification of complexity. As mentioned in the previous section, some of these studies utilized the factors defined in the complexity frameworks. For example, the aforementioned framework of Vidal and Marle (2008) served to develop a comparative index for the complexity scores of different projects (Vidal, Marle, & Bocquet, 2011). Seventy complexity factors determined via this framework were refined with an international Delphi study, which resulted in obtaining two “technological” and 15 “organizational” complexity factors. Then, by prioritization of these factors with the Analytic Hierarchy Process (AHP), a “relative project complexity index” was developed. Similarly, Nguyen et al. (2015) employed fuzzy AHP to obtain the weights of the 18 complexity factors in transportation projects under the groups of “scope,” “technological,” “infrastructural,” “organizational,” “environmental,” and “sociopolitical.” The weighted factors were then assigned a complexity score with a scale of 0-10 to measure the overall complexity level of projects. Mirza and Ehsan (2016) collected data from 149 projects to measure the complexity of three main performance criteria in projects. For this purpose, they specified 10 factors for “time complexity,” 42 factors for “scope complexity,” and eight factors for "cost complexity." Based on the statistical analyses of these factors, they developed a "project execution complexity index" customized for research and development, infrastructure, and other projects. Kian Manesh Rad, Sun, and Bosché (2017) developed a taxonomy of 10 "external indicators" and 41 "internal indicators" related to the complexity of megaprojects in the energy sector. By establishing the weights of these indicators with the Delphi and AHP group decision-making method, a complexity index that assesses the internal and external complexity scores of projects was introduced. Most recently, Poveda-Bautista, Diego-Mas, and, Leon-Medina (2018) identified 58 factors in 11 categories for Information Technology (IT) projects by modifying the complexity assessment system implemented by the International Project Management Association (IPMA) to certify the competency in managing complex projects. Then, they developed a "Complexity Index Tool" to assess the complexity level of these factors and their contribution to the project complexity.

On the other hand, some researchers preferred to quantify the complexity with more inclusive groups. Xia and Chan (2012) conducted a Delphi study to formulate a complexity index, which measures the complexity in building projects with the weighted parameters consist of "building structure and function," "construction method," "schedule urgency," "project size/scale," "geological condition," and "neighboring environment." Gransberg, Shane, Strong, and, del Puerto (2013) calculated the "complexity footprint" score of the transportation projects by rating the "technical," "schedule," "cost," "context," and "financing" dimensions. de Carvalho, Patah, and de Souza Bido (2015) scored the "financial," "contractual," "technical complexity," and "organizational considerations" criteria to categorize 1387 projects based on their complexity.

There are also some studies that quantified the project complexity over the activity networks. For instance, Nassar and Hegab (2006) developed a measure considering the number of activities and arcs between them in the Activity-on-Node (AoN) networks to calculate the complexity of the project schedules. Later, Bashir (2010) improved this measure using a graph theory approach that removes the redundant relationships in the network. Finally, Ellinas, Allan, and Johansson (2018) utilized the “degree centrality,” “betweenness centrality,” “daily task density,” and “inter-event time” indicators in activity networks to measure the “structural complexity” of five engineering projects.

2.1.5 Managing Complexity

Due to the impact of complexity on project performance, there is a need for appropriate management approaches. For most of the researchers, complexity is a negative term, and it has a detrimental impact on the projects (Luo et al., 2017; Maylor, Turner, & Murray-Webster, 2013; Montequín et al., 2018). For example, based on the empirical analysis of five case studies, Antoniadis, Edum-Fotwe, and Thorpe (2011) asserted that “socio-organo complexity” that caused by the interconnections between the project team members has an inverse correlation with the project schedule performance. The term complexity is usually thought of as a negative concept by the practitioners as well. According to Geraldi (2009), some project teams not only associate complexity with the terms such as “undesirable,” “complicated,” and “difficult” but also use it as an “excuse for mistakes.” Nonetheless, some researchers believe that complexity may not always lead to negative events. According to Vidal and Marle (2008), complexity may have a positive influence on the project system by promoting the emergence of opportunities. Similarly, Floricel et al. (2016) stated that complexity-related difficulties might stimulate the managers to develop more suitable strategies for coping with them. A high level of complexity may also be a catalyst for innovation in the projects (Brockmann, Brezinski, & Erbe, 2016). Although there are different opinions regarding its effects on project performance, it is evident that complexity requires a management effort. In this sense, researchers developed different approaches to manage project complexity, as described below.

In many studies, new complexity management practices, frameworks, or models were recommended based on observations made in in-depth case studies. In one of these studies, Koppenjan, Veeneman, van der Voort, ten Heuvelhof, and Leijten (2011) explained how complexity and uncertainties could be managed in large engineering projects. Accordingly, they developed a framework that explains the competing management approaches, namely “predict-and-control” and “prepare-and-commit.” The first put a strong emphasis on strict planning and control, while the latter focuses on flexibility and responsiveness. The authors suggested balancing these approaches by explaining the application of this framework to the RandstadRail project in The Netherlands. In another study, Davies and Mackenzie (2014) elucidated how system integration could be achieved for the SoS, which is decomposed into smaller systems to cope with complexity. They exemplified the challenges related to the system- and meta systems-level integration over the case study of the London Olympics and Paralympics 2012 construction program. In order to reduce the complexity of infrastructure megaprojects, Zhang and Qiu (2018) suggested an improved Design-Build (DB) project delivery system that gives more flexibility to the owner to interfere in the construction consortium. The application of the new DB mode was demonstrated through the Hong Kong-Zhuhai-Macao Bridge project in China. With another case study of the same project, Mai, Gao, An, Liu, and Liu (2018) introduced a “meta-synthesis management framework” to reduce the complexity in design and construction phases. The framework is based on transforming the complex problems into systematic problems with the “exploration” strategy and improving the efficiency of the project management methods with the “exploitation” strategy. Furthermore, Hu, Le, Gao, Li, and Liu (2018) explained the role of “co-evolution between governments and markets” in treating the “institutional complexity” with an inductive case study of the same project. With the same objective, Matinheikki, Aaltonen, and Walker (2019) recommended forming a project alliance organization between the bureaucratic state, corporate market, and multiple professions to deal with the “institutional complexity” caused by their conflicting demands. They demonstrated how a “temporary hybridization” was realized in the Lakeside Tunnel Project.

There are also some studies that assessed the efficiency of different management approaches with statistical analyses. For instance, based on the data collected from 45 large-scale engineering and construction projects, Ahn et al. (2017) established the positive impact of "interface management tools/practices" on reducing the complexity factors related to "scope," "communication," and "number of stakeholders." In another study, Gao, Chen, Wang, and Wang (2018) tested several hypotheses by analyzing data of 180 questionnaires with SEM to evaluate the role of contractual functions in project complexity. Accordingly, they identified the efficiency of "coordination," "adaptation," and "control" functions of the contract in terms of addressing the "technical," "organizational," and "environmental" complexity categories of the TOE framework.

On the other hand, some researchers emphasized the need for more fundamental changes to manage complexity in projects. Jaafari (2003) questioned the validity of conventional project management practices by claiming that they are not suitable to respond to the challenges of the complex society. The author called for a paradigm shift in project management and proposed a "creative-reflective" project management model to tackle high environmental complexity characterized by "open systems," "chaos," "self-organisation," and "interdependence." According to Thomas and Mengel (2008), the current approaches in project management education should put more emphasis on the "softer" aspects to develop "emotionally and spiritually intelligent" project managers. In this respect, they listed "shared leadership," "social competence and emotional intelligence," "communication," "skills in organizational politics," "visions," "values," and "beliefs" as required competencies to deal with "complexity," "chaos," and "uncertainty."

Consequently, studies discussed in this section reflect very different approaches developed to manage project complexity. However, the number of studies that address the complexity as a part of the project risk management process is scarce. In this regard, the next section elaborates on the relationship between complexity and risk-related concepts by reviewing the related literature.

2.1.6 Complexity as a Risk-Related Concept

In order to have a better understanding of their relationship, the conceptual similarities and differences between complexity and risk have to be clarified. Project Management Body of Knowledge (PMBOK) Guide (PMI, 2017, p. 720) defined risk as “an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives.” According to this definition, complexity and risk have some similarities in terms of their impact on project performance. However, the main difference between these concepts is that while risk concerns possible future situations, complexity is related to the factors that make the current situation complex (Geraldi, 2009). Qazi et al. (2016) associated complexity with “known” attributes of the project and considered it as the source of the risks, which are categorized as “known unknowns” and “unknown unknowns.” From this point of view, both complexity and actions taken to deal with complexity may affect the project objectives and thus result in risk events. On the other hand, the risk definition of the PMBOK suggests that uncertainty is also a source of risk events. There are two types of uncertainties that can trigger risk events in projects. The “aleatory uncertainty” refers to stochastic variations in the future state of a parameter, whereas the “epistemic uncertainty” pertains to vagueness caused by imperfect information or lack of knowledge (Aven, 2016). Therefore, from the project management point of view, the former means the uncertainty about the future, while the latter represents the vagueness about the project.

The review of complexity and uncertainty concepts revealed that they might affect the risk events in a similar manner. Conceptual similarities between complexity and uncertainty caused the intermingling of these terms in the project management literature (Padalkar & Gopinath, 2016). In this respect, two main research approaches have been raised to explain their causality. According to the first school of thought, uncertainty is a driver of project complexity, as discussed in Section 2.1.2 (Dunović et al., 2014; Geraldi et al., 2011; Williams, 1999). It may lead to more dynamics and interactions that increase the overall complexity level in the project system. In contrast to this view, some studies considered uncertainty as a consequence of project complexity (Floricel et al., 2016; Vidal & Marle, 2008). Researchers of this stream believe that complexity may result in a more unpredictable project system, which increases the uncertainty. There is also a lack of consensus regarding the relationship between complexity and risk. In some studies, complexity was accepted as the source of risk events (Qazi et al., 2016), while it was conceptualized as the outcome of project risk in some other studies (Bosch-Rekveldt et al., 2011). All of these perspectives explaining the complexity-uncertainty and complexity-risk relationships have merit, and they may help to model the interactions between risk-related concepts in a reliable way, which is one of the aims of project risk management. However, project management literature lacks the structured synthesis of these concepts (Thomé et al., 2016). Although the interdependencies between risk-related concepts are evident, existing studies towards modeling the interactions usually handled the complexity and risk separately.

There are many studies in the literature devoted to modeling the interactions between risk factors. These studies usually adopted network-based analysis or risk mapping techniques. For example, Fang, Marle, Zio, and Bocquet (2012) utilized the network theory to reflect the interactions between risk factors and compared the topological analysis with the traditional risk rating, which is based on the multiplication of probability and impact scores. The study of Fang and Marle (2012) not only incorporated the network analysis techniques into the traditional risk rating but also used the discrete-event simulation to evaluate the influences of risk response actions. Based on the same model, Fang, Marle, and Xie (2017) developed new “importance measures” to prioritize the interconnected risks. The proposed metrics were tested by simulating the 56 risks identified in a tramway project. In addition to these studies, there are network-based risk management approaches combined with different techniques. Zhang (2016) proposed an optimization model to select the most appropriate risk response strategies considering the interdependencies in a risk network. Qazi and Dikmen (2019) utilized a data-driven Bayesian Belief Network (BBN) methodology to model the interactions in a risk network using the “propagation,” “vulnerability,” and “resilience” concepts. Yazdani, Abdi, Kumar, Keshavarz-Ghorabaee, and Chan (2019) developed a fuzzy Analytic Network Process (ANP) model to reflect the relationships among “technical,” “external,” and “internal” risk factors in construction projects. On the other hand, studies based on risk mapping usually designated the paths of risk events that affect the project objectives. In this respect, Fidan, Dikmen, Tanyer, and Birgonul (2011) developed an ontology to identify the causal relations between risk-related concepts and project cost overrun. They constructed a database structure to store the paths between “risk sources,” “risk events,” and “risk consequences” along with “vulnerability factors” that interfere with these paths. Based on this ontology, Eybpoosh, Dikmen, and Birgonul (2011) analyzed the data obtained from 166 projects with SEM to assess the impact of 36 risk paths and related vulnerability factors on the cost overrun of international construction projects. With a similar method, J. Liu, Zhao, and Yan (2016) identified 20 risk paths that have a significant impact on cost, quality, and schedule objectives of the international construction projects performed by Chinese contractors. Additionally, by combining the findings of Fidan et al. (2011) and Eybpoosh et al. (2011), Yildiz, Dikmen, Birgonul, Ercoskun, and Alten (2014) developed a “knowledge-based risk mapping tool” that helps to estimate the cost of international construction projects. The mapping techniques can also be used to draw a more comprehensive risk picture during risk analysis. Ackermann, Howick, Quigley, Walls, and Houghton (2014) used causal maps in group decision-making to elicit the impact of the risk interactions from the point of view of diverse stakeholders. Moreover, these maps can provide a basis for quantitative modeling techniques, such as System Dynamics (SD) (Ackermann & Alexander, 2016; Williams, 2017).

Despite the abundance of studies on risk interdependency, modeling the interactions between the complexity factors did not receive too much attention in the project management literature. According to Geraldi et al. (2011), the interdependencies between the complexity factors is an emerging research topic. Similarly, Zhang and Qiu (2018) highlighted the importance of considering the relationships among the complexity factors throughout the life cycle of a project. Nevertheless, with a few exceptions, most of the studies related to the complexity factors in Sections 2.1.3 and 2.1.4 did not consider their interrelations. Among these exceptions, Qureshi and Kang (2015) and Luo et al. (2017) paid attention to the relationship between different complexity factors thanks to SEM, whereas Montequín et al. (2018) used self-organizing maps to cluster the factors related to each other. In addition to these studies, Danilovic and Browning (2007) developed an approach that uses "design structure matrix" and "domain mapping matrix" together to identify the dependencies within and across the five complexity domains of product development projects.

As a summary, the issue of interdependency has been mentioned by various studies, especially related to the risk factors. These studies contributed to the existing knowledge by offering useful insights into modeling the interactions. However, there are only a limited number of studies that model the relationships between risk-related concepts. The Project Complexity and Risk Management (ProCRiM) process proposed by Qazi et al. (2016) is one of the studies that considered the interdependency between complexity and risk. According to the ProCRiM process, complexity categories of the TOE framework are the source of various risk factors, which affect the project objectives and overall utility. The quantification of the ProCRiM process was achieved by combining BBNs, which model the interactions, and the expected utility theory, which calculates the preferences of the decision-maker concerning the project objectives. In addition to this study, Dikmen et al. (2020) recently proposed a meta-modeling approach to capture the non-linear interactions among the "complexity-uncertainty-performance triad" in construction projects. The meta-model initially utilizes BBNs to account for complex interdependencies across the triad. Then, the Shapley value from Game Theory establishes the relative contribution of complexity and uncertainty factors to project performance by considering the mediating role of management strategies as well. Finally, Artificial Neural Networks (ANNs) helps to predict project performance.

Even though the aforementioned studies utilized advanced techniques to model the relationships between risk-related concepts, they may not be suitable to represent multi-level interactions specific to megaprojects. Developing modeling approaches exclusive to megaprojects has particular importance since they are characterized by complexity and risk because of their unique features (Kardes et al., 2013). In this respect, the following section presents a comprehensive review of megaprojects to shed more light on these features.

2.2 Megaprojects

Megaprojects have been a source of growing interest among a diverse group of actors, including researchers, practitioners, politicians, and the community in recent years. According to Flyvbjerg (2014), the annual megaproject spending that constitutes 8% of the total global Gross Domestic Product (GDP) is “the biggest investment boom in human history.” In accordance with the increasing global popularity, the megaprojects have become an attractive research topic in the field of project management as well. Ever since the term was first used in 1976 (Li, Lu, Taylor, & Han, 2018), the number of publications on megaprojects has shown a dramatic increase, especially after the 2000s (Pollack, Biesenthal, Sankaran, & Clegg, 2018).

The reason why megaprojects get so much attention can be explained by their double-edged impact on society. On one side, they have the potential to contribute to the local and national economy by providing urban development, creating employment opportunities, improving technology, and leading to the formation of other industries (Cheung & Shen, 2017; Jia, Yang, Wang, Hong, & You, 2011b; Ma, Zeng, Lin, Chen, & Shi, 2017). Furthermore, they can be attributed as the modern symbols of “prestige,” “progress,” and “political power” by the nations (van Marrewijk, 2017). Hence, megaprojects continue to get built in the form of “infrastructure (e.g., airports, high-speed rail lines, motorways),” “superstructure (e.g., hospitals, high-rise buildings, signature architecture),” “water structures (e.g., dams, seaports)," "energy structures (e.g., wind farms, power plants, oil and gas extraction)," and "mega events (e.g., Olympic Games, World Expos)" (Erol, Dikmen, Atasoy, & Birgonul, 2018). On the other side, depending on their performance, they may also cause irreversible damage (Hu, Chan, Le, Xu, & Shan, 2016). The magnitude of these projects makes them more vulnerable to cost overruns (Callegari, Szklo, & Schaeffer, 2018), which can put the financial situation of the companies at risk and even threaten the economic stability of the countries (Eweje, Turner, & Müller, 2012). Moreover, due to their economic significance, rent-seeking behavior and corruption issues are common in megaprojects (Flyvbjerg, 2014; Veenswijk, van Marrewijk, & Boersma, 2010). Their detrimental impact on the environment and society is another important issue, which often leads to public opposition (Capka, 2004).

In order to deal with the challenges of the megaprojects, a better understanding of their nature is needed. In this respect, the subsequent sections discuss a variety of topics in literature. The review starts with the compilation of several definitions proposed by researchers. Since most of the descriptions include monetary terms, the cost thresholds of megaprojects are investigated in the next section. Then, other essential features of the megaprojects are explored. After discussing their performance issues, this part is concluded with the management of complexity and risk in megaprojects, which constitutes the main focus of the research.

2.2.1 Definition of Megaproject

The researchers have used the terms "megaproject," "teraproject," "gigaproject," "major project," "large project," and "complex program" interchangeably to describe the megaprojects (Zhou & Mi, 2017). There are also different definitions that emphasize the various aspects of megaprojects in the literature. Some of these definitions are compiled in Table 2.2.

Table 2.2. Definitions of Megaprojects
(adapted from Erol et al., 2018)

Megaproject Definition	Reference Study
". . . projects which transform landscapes rapidly, intentionally, and profoundly in very visible ways, and require coordinated applications of capital and state power" (pp. 15-16).	Gellert and Lynch (2003)
". . . major infrastructure projects that cost more than $1 billion, or projects of a significant cost that attract a high level of public attention or political interest because of substantial direct and indirect impacts on the community, environment, and State budgets" (p. 4).* *According to the Federal Highway Administration in the United States	Capka (2004)
"A construction project, or aggregate of such projects, characterized by: magnified cost, extreme complexity, increased risk, lofty ideals, and high visibility, in a combination that represents a significant challenge to the stakeholders, a significant impact to the community, and pushes the limits of construction experience" (Megaproject Definition, para. 3).	Fiori and Kovaka (2005)
". . . multibillion-dollar mega-infrastructure projects, usually commissioned by governments and delivered by private enterprise; and characterized as uncertain, complex, politically-sensitive and involving a large number of partners" (p. 591).	van Marrewijk, Clegg, Pitsis, and Veenswijk (2008)
". . . large-scale, complex ventures that typically cost US$1 billion or more, take many years to develop and build, involve multiple public and private stakeholders, are transformational, and impact millions of people" (p. 6).	Flyvbjerg (2014)
". . . projects with contract sums over HK$1 billion, involving a huge number of participants, having significant social and economic impacts, extensive works, large geographical coverage and close connection to other major developments" (p. 446).* *According to the Development Bureau in Hong Kong	Mok, Shen, and Yang (2015)

Although all the reference studies in Table 2.2 described megaprojects in monetary terms, they have different focal points. For instance, Gellert and Lynch (2003) underlined the destructive impacts, whereas Fiori and Kovaka (2005) focused on characteristic features, such as complexity and risks. Thus, the following two sections elaborate on the cost thresholds and other features of megaprojects to cover the subjects mentioned in the definitions.

2.2.2 Cost Thresholds for Megaprojects

Most of the definitions in Table 2.2 recommended the 1 billion dollars as the minimum cost of the megaprojects. Although it is a widely accepted number, there are a variety of opinions in terms of cost thresholds of megaprojects. For example, Brookes and Locatelli (2015) reported that \$100 million could be considered as a mega-size, depending on the project context. From a different perspective, some researchers argue that the threshold value might alter according to the economic situation of the country where the project is performed. Hu et al. (2015b), for instance, proposed to consider the ratio between the project cost and GDP of the country. The cost threshold values suggested in several studies are listed in Table 2.3.

Table 2.3. Cost Threshold Values of Megaprojects
(adapted from Erol et al., 2018)

Cost Threshold	**Reference Study**
\$100 million	Brookes and Locatelli (2015)
€100 million* *According to the International Project Management Association for countries in the European Union	Hu et al. (2015b)
HK\$1 billion* *According to the Development Bureau in Hong Kong	Mok et al. (2015)
€250 million* *for small and medium-sized European countries	Mišić and Radujković (2015)
\$300 million	Eweje et al. (2012)
\$500 million* *According to the Federal Highway Administration in the United States	Hu et al. (2015b)

Table 2.3. (Cont'd) Cost Threshold Values of Megaprojects
(adapted from Erol et al., 2018)

Cost Threshold	**Reference Study**
$500 million	Biesenthal, Clegg, Mahalingam, and Sankaran (2018)
¥5 billion* *According to the National Development and Reform Commission in China	Hu et al. (2015b)
$1 billion	Capka (2004); Flyvbjerg (2014); Han et al. (2009); Jergeas and Ruwanpura (2010); Kumaraswamy (1997); Rolstadås, Tommelein, Schiefloe, and Ballard (2014)
United States: 0.01% of GDP EU Countries: 0.02% of GDP China: 0.01% of GDP Hong Kong: 0.01% of GDP South Korea: 0.05% of GDP	Hu et al. (2015b)

2.2.3 Characteristic Features of Megaprojects

Even though the cost is the primary factor in deciding whether a project "mega" or not, it cannot be the only feature that characterizes the megaprojects. According to Pollack et al. (2018), the real mark of a megaproject is the existence of features like "organizational complexity," "ambiguity," "ambition," "politicality," and "risk." They advocated that an expensive project may not have these features, whereas a relatively low-budget project may be "complex," "ambiguous," "ambitious," "political," and "risky." Hence, all related aspects should be taken into consideration when a megaproject is described. In this respect, this section covers the characteristic features of megaprojects, other than cost.

Due to their size, megaprojects are also characterized by the expenditure of an enormous amount of human, material, financial, and technological resources over a long period (Biesenthal et al., 2018; Capka, 2004). Furthermore, it may not be easy to predict the amount of these resources because the needs of the owner and other stakeholders may change during the extended project life cycle (Flyvbjerg, 2009). The scope creep caused by the dynamic nature of megaprojects may result in additional resource requirements.

Another important feature is the number of stakeholders involved directly and indirectly in megaprojects. Interfaces and interdependencies between the owner, contractor, consultants, designers, subcontractors, sponsors, suppliers, government, public, and other hidden stakeholders increase the managerial difficulty. Moreover, minimizing the conflict that stems from divergent and opposite interests of these actors requires complex contractual arrangements (Wu, Zhao, Zuo, & Zillante, 2018). For this reason, establishing robust communication strategies between diverse stakeholders is a vital task in megaprojects (Pitsis, Clegg, Freeder, Sankaran, & Burdon, 2018).

Attracting a high level of public and political interest is another defining feature of the megaprojects. According to Chapman (2016), this interest can be explained by their influence on the "environment," "ecology," "economy," "neighboring communities," and "property owners." The political attention is also related to the prominence of these projects. Capka (2004) stated that politicians might exploit megaprojects to gain a personal reputation before the elections. Political interventions may influence them substantially by recasting the project context (Dimitriou et al., 2013).

Megaprojects are also the source of social and environmental concerns, including "anti-corruption," "ecological protection," "disaster mitigation," "immigrant settlement," "occupational health and safety," "pollution control," and poverty eradication" (Ma et al., 2017). Taking these subjects into account is essential in managing the megaprojects. To illustrate the significance of social issues, Z. Liu, Zhu, Wang, and Huang (2016) explained the conflicts, which resulted in eight deaths and 18 injuries, in an urbanization program related to the relocation of 100 million people in China. On the other hand, as the definition of Gellert and Lynch (2003) in Table 2.2 implies, megaprojects may also destroy the biological, geological, and physical attributes of the environment. For example, Stone (2011) reported that mitigating the environmental impacts of the Three Gorges Dam, the world's largest hydropower project, is estimated to cost $26.45 billion, which is greater than the budget of many megaprojects. Consequently, the social and environmental responsibility of the megaprojects requires particular policies and practices that should be conducted throughout the whole project life (Ma et al., 2017).

Finally, the existence of complexity and risk is a natural outcome of the features discussed above. There is an overwhelming consensus among the project management scholars that complexity is an inherent part of the megaprojects (Capka, 2004; Pitsis et al., 2018; van Marrewijk & Smits, 2016). According to Hu et al. (2015b), mega construction projects are theoretically complex projects due to their characteristic features. On the other hand, Boateng et al. (2015) indicated that megaprojects are confronted with unique risks driven by "social," "technical," "economic," "environmental," and "political" challenges.

Managing complexity and risk, together with the characteristics that trigger their emergence, is a challenging task for the managers of megaprojects. For this reason, performance problems are common in these projects. The next section discusses performance issues in megaprojects to emphasize the shortcomings of the current management practices.

2.2.4 Performance Issues in Megaprojects

This section is composed of two main parts. In the first part, some statistics depicting the poor performance of the megaprojects are provided. Then, in the second part, the main reasons for the underperformance of the megaprojects are discussed.

2.2.4.1 Performance Statistics

There are many studies in the literature that explain the performance issues of the megaprojects with statistical terms. In one of these studies, Flyvbjerg, Holm, and Buhl (2003b) performed a detailed analysis of the 258 transport infrastructure projects held in 20 countries within a time span of 70 years. According to the reported results, the average difference between the actual and estimated costs of these projects is 27.6%. In alignment with this result, the average cost overrun of 30 mega transportation projects worth $138.9 billion in 10 developed countries was found to be 22%, and half of them were delivered at least one year later than planned (Dimitriou et al., 2013). Energy projects also suffer from the same kind of performance issues. Statistical analysis of Callegari et al. (2018) for 401 mega power plant projects carried out between 1936 and 2014 in 57 countries demonstrated that 75.3% of them exceeded the budget, while 55.9% of them completed later than planned. Table 2.4 presents the performance statistics obtained from the literature for some megaprojects across the world.

Table 2.4. Performance Statistics for the Selected Megaprojects

Project	Cost Overrun	Schedule Delay	Reference Study
Amsterdam Metro North-South Line – The Netherlands	€1.7 billion	≈ 6 years	Smits and van Marrewijk (2012)
Boston Central Artery/Tunnel (Big Dig) – United States	$12 billion	≈ 3 years	Boateng et al. (2015)
East-West Highway – Algeria	> $4.2 billion	> 5 years	Zidane, Johansen, and Ekambaram (2015)
Edinburgh Tram Network – Scotland	£0.401 billion	3.5 years	Boateng et al. (2015)
Korea Train Express – South Korea	$12.6 billion	5.5 years	Han et al. (2009)
Millau Viaduct – France	-$0.13 billion (under budget)	No Delay	Locatelli, Invernizzi, and Brookes (2017)
The Channel Tunnel Rail Link – England	$3.23 billion	≈ 4 years	Locatelli et al. (2017)

With one exception, all projects listed in Table 2.4 experienced performance problems. Despite their poor performance, megaprojects continue to get built, which is called the “megaproject paradox” (Flyvbjerg, Bruzelius, & Rothengatter, 2003a). For this reason, the main factors contributing to the performance problems must be identified so that more effective management approaches can be developed for future megaprojects.

2.2.4.2 Reasons for the Performance Problems

There are different approaches in the literature to explain the performance problems of the megaprojects. With a thorough discussion of these approaches, Sanderson (2012) identified three types of explanation for the performance problems, which are “strategic rent-seeking behaviour,” “misaligned and underdeveloped governance,” and “diverse project cultures and rationalities.” Based on Sanderson’s typology, the factors that cause poor performance in megaprojects, as well as studies related to the management of these factors, are scrutinized below.

According to the first type, the performance problems are caused by unrealistic estimates of the decision-makers during the project development stage. In other words, there is a tendency to underestimate the costs and overestimate the benefits. Some researchers argue that biased predictions may arise from honest mistakes related to psychological factors, such as “optimism bias” (Giezen, 2012). For instance, Kardes et al. (2013) utilized the concepts of the “illusion of control,” “the sunk cost effect,” “prospect theory,” and “self-justification theory” to explain the psychological factors in decision-making. In contrast to this argument, Flyvbjerg, Holm, and Buhl (2002) claimed that the cost underestimation is best explained by “strategic misrepresentation, that is, lying.” Based on the statistical analysis of 258 transport infrastructure projects, they refused the psychological and technical explanations. According to Giezen (2012), the reason why decision-makers intentionally misrepresent the estimates is that projects would have never been built in case their costs were announced with real figures. For this reason, instead of the best projects, the alternatives that look best on paper getting funded, which is called the "survival of the unfittest" (Flyvbjerg, 2009). According to Sanderson (2012), legal regulations are required to cope with the performance problems related to the first type. To illustrate how to reduce inaccuracy and bias in the project development stage, Flyvbjerg (2009) recommended using the "reference class forecasting method" that improves the accuracy of the cost estimates with the help of historical data. With a similar approach, Locatelli and Mancini (2010) adopted a nine-step framework to prevent overestimation of the benefits.

The second type of explanation for the performance problems puts more emphasis on governance mechanisms. Although the arguments proposed by Flyvbjerg et al. (2002) are widely accepted in the literature, Love and Ahiaga-Dagbui (2018) heavily criticized them in order to draw more attention to the project management issues. In this respect, researchers have developed several theories, frameworks, models, and tools to improve the organizational and managerial performance of the megaprojects. For example, Jia et al. (2011a) introduced the Program Management Organization Maturity Integrated Model (PMOMIM) to solve problems in organizational management and process management of mega construction programs. Hu et al. (2012) demonstrated how contractual incentives in the Shanghai Expo construction enhanced management performance to accomplish the safety, quality, and environmental goals. Shokri, Ahn, Lee, Haas, and Haas (2016) reported that systematic interface management practices in megaprojects improve both the communication between the stakeholders and the cost performance of the project. Finally, Zhou, Wang, and Zeng (2018) proposed an IT-based smart construction site framework, which integrates computer technologies, such as Cyber-Physical Systems (CPS), big data, Building Information Modelling (BIM), and cloud computing into the mega construction projects.

Finally, the third type of explanation for the performance problems underlines the importance of the project cultures. By refusing the systematic underestimation view proposed by Flyvbjerg et al. (2002), van Marrewijk et al. (2008) argued that the performance problems of the megaprojects are more closely associated with the cultural characteristics of the project organizations. According to Biesenthal et al. (2018), megaprojects should be treated with a socio-technical perspective since problem areas in these projects go beyond the technical issues. In this sense, there are also studies pertain to social and cultural practices in megaprojects. For instance, Veenswijk et al. (2010) stressed the role of public-private collaboration in the Dutch construction sector in developing new forms of learning for the megaprojects. Based on an ethnographic field study of the Panama Canal Expansion megaproject, which was performed by a consortium of Spanish, Italian, Belgian, and Panamanian construction companies, van Marrewijk and Smits (2016) identified the cultural practices that affect project governance. Finally, van Marrewijk (2017) explained how symbolic meanings of a megaproject might result in power struggles, delays, and cost overrun if they are interpreted differently by the stakeholders.

Consequently, researchers have developed various management approaches for the problem areas identified by Sanderson (2012). Despite their fundamental differences, most of them consider the complexity and risk as critical issues of megaprojects. For this reason, there is a need to put more emphasis on risk-related studies in megaproject research. According to Dimitriou et al. (2013), risk, uncertainty, and complexity are at the heart of decision-making in megaprojects. Unique problems of megaprojects can be overcome by developing effective risk management practices that incorporate these concepts (Kardes et al., 2013). Thus, existing studies related to managing complexity and risk in megaprojects, as well as their shortcomings, are covered in the next section.

2.2.5 Managing Complexity and Risk in Megaprojects

The complexity and risk topics have been investigated in several studies related to the megaprojects. In an attempt to assess the complexity of mega construction projects, He, Luo, Hu, and Chan (2015) developed a fuzzy ANP model that measures the complexity scores of the “organizational,” “cultural,” “environmental,” “technological,” “information,” and “goal” dimensions. Some researchers proposed new complexity frameworks or models specific to megaprojects. For example, Chapman (2016) introduced a comprehensive complexity framework for rail megaprojects. Besides the complexity dimensions, including “delivery,” “management,” “task,” “finance,” “site,” and “context,” the framework contains other factors that may influence the complexity due to the dynamic project environment. On the other hand, there are also studies that focused on risks related to megaprojects. In this context, Boateng, Chen, and Ogunlana (2017) combined ANP and SD techniques to both prioritize and simulate the “social,” “technical,” “economic,” “environmental,” and “political” risks in the Edinburgh Tram Network megaproject. Most recently, Owolabi et al. (2020) developed a regression model to estimate “bankable completion risk” in Public-Private Partnership (PPP) megaprojects from the perspective of the financiers.

It is evident that the aforementioned studies addressed different aspects related to complexity and risk in megaprojects. However, the management of complexity and risk has not been synthesized in these studies. Treating complexity and risk as independent concepts can hardly deal with the challenges emanating from their multi-level interactions. With a few exceptions, the literature lacks studies oriented to explore the relationship between complexity and risk. Among these exceptions, Kardes et al. (2013) developed a risk management framework for megaprojects and offered managerial prescriptions to address the complexity. Giezen (2013) introduced “adaptive capacity” and “strategic capacity” concepts and their role in reducing complexity and uncertainty in megaprojects. In addition to these studies, Dimitriou et al. (2013) advised on managing the risk, uncertainty, and complexity by reporting the findings from case studies of the 30 international mega transportation projects. Notwithstanding the useful insights offered by these studies, how complexity shall be positioned within the risk management process of megaprojects remains an important question that requires further research efforts.

2.3 Research Gap

As a summary, studies reviewed in the previous two sections handled various issues regarding complexity, risk, and their role in the megaprojects. Despite the invaluable contributions of these studies to the body of knowledge, there are still some limitations that create a research gap in the project management literature. First, studies that addressed the causality between complexity and risk-related concepts in different ways do not provide a consistent explanation for their relationship. The ambiguous links between complexity and risk should be clarified with further research. Second, existing studies offer disintegrated approaches to manage project risk and complexity. There is a need for developing alternative methods to treat complexity as a component of risk management processes. Third, despite the abundance of studies towards the quantification of complexity, the number of studies that measure the impact of complexity on risks is quite limited. New analytical models that can quantify the risks by taking the complexity factors into account are required for megaprojects in particular due to their apparent relevance to these concepts. Fourth, even though some of the studies mentioned in the previous sections employed case studies to test the proposed management approaches, the project management literature fails to reflect the empirical reality of megaprojects in terms of treating complexity and risk collectively. More research is needed to report the practical benefits of using integrated approaches in megaprojects.

Consequently, the research questions presented in Section 1.2 have emerged as a consequence of the research gap identified in the project management literature. In order to address these questions and thus fill the research gap, an exploratory study towards untangling the nature of the relationship between complexity and risk in mega construction projects was conducted as an initial step. Then, a conceptual model was proposed to integrate complexity into risk management of mega construction projects. Later on, the conceptual model was put into practice with an analytical model to quantify the risks of mega construction projects based on the complexity factors. Finally, the proposed approach was tested with real projects to report empirical findings. The next chapter describes the methodology employed for these studies.

CHAPTER 3

RESEARCH METHODOLOGY

In order to accomplish the objectives of this study, a research methodology consisting of the following three main phases has been embraced.

- **Phase 1:** Based on a mixed-methods research approach, quantitative and qualitative data collected from 11 megaprojects through interviews with 18 participants were analyzed to conceptualize the relationship between complexity and risk. Correspondingly, a process model was proposed for the risk assessment of mega construction projects by integrating the quantitative and qualitative findings.
- **Phase 2:** The conceptual risk assessment model proposed in the previous phase was operationalized through an analytical model. In this respect, an Analytic Network Process (ANP)-based model was developed for risk quantification in mega construction projects by eliciting expert knowledge through a two-round Delphi study.
- **Phase 3:** Testing and validation studies were performed for the ANP model and the proposed risk assessment process by revisiting the findings of 11 megaprojects and conducting a demonstrative case study.

The steps of the research are demonstrated in Figure 3.1. The subsequent sections present the details of the three phases.

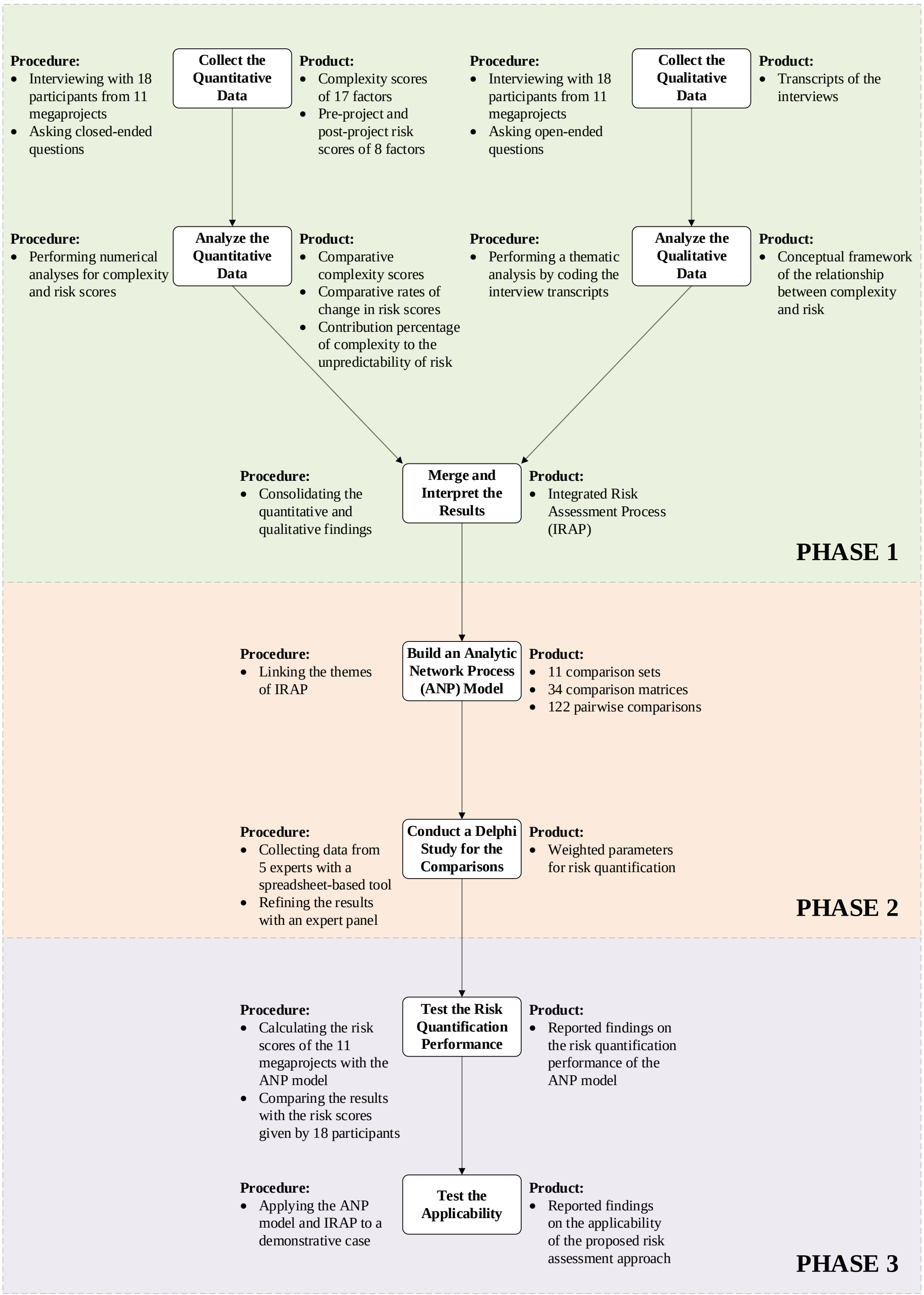


Figure 3.1. Overview of the Research Design

3.1 Phase 1: Conceptual Risk Assessment Model

The first phase constitutes the core of this research as it forms a basis for the proposed risk assessment approach. With the purpose of establishing a robust methodology in this phase, a mixed-methods research approach was adopted. From a methodological perspective, the mixed-methods is a type of research that combines quantitative and qualitative approaches in the research design (Tashakkori & Teddlie, 1998). A convergent design was used to place equal emphasis on quantitative and qualitative parts. According to this design, quantitative and qualitative data are collected concurrently, analyzed separately, and their results are merged (Creswell & Plano Clark, 2017). The rationale for the integration is ensuring a better contextual understanding since qualitative evidence can assist quantitative survey data in uncovering the relationships among variables (Bryman, 2006). For this reason, mixed-methods research has been employed in several studies related to complexity, risk, and megaprojects (Bosch-Rekveldt et al., 2018; Hu, Chan, & Le, 2015a; Keers & van Fenema, 2018).

The mixed-methods approach utilized in this study was based on collecting quantitative and qualitative data through interviews with 18 participants from 11 mega construction projects. Collected data were analyzed in both ways to have far-reaching results. The quantitative analysis helped to correlate the complexity and risk numerically, whereas the qualitative analysis served to develop a conceptual framework that explains their relationship. Integrating the quantitative and qualitative findings resulted in the development of a new risk assessment process that can capture the relationship between risk-related concepts. The following sections clarify the data collection, data analysis, and integration procedures.

3.1.1 Data Collection

The first step of the data collection process was the identification of complexity and risk factors to be included in the interview protocol. Then, projects that constitute the sample of the research were determined. At the last step, interviews were conducted with the managers of these projects. The steps of the data collection process are detailed in the following three sections.

3.1.1.1 Identification of Complexity and Risk Factors

Since there is no widely accepted taxonomy for megaproject complexity and risk, factors to be included in the interview protocol were selected based on an in-depth literature review. For this purpose, frameworks developed by various researchers were reviewed to prepare an initial list of complexity and risk factors. As discussed in Section 2.1.3, there are many complexity frameworks in the literature. Among them, the Technical, Organizational, and Environmental (TOE) framework, developed by Bosch-Rekveldt et al. (2011) for large engineering projects, is believed to be the most suitable framework for the complexity factors of mega construction projects. Therefore, it was accepted as the base framework of this study. There are also numerous risk factors relevant to mega construction projects. A structured classification of these factors may help to understand their characteristics and sources better and reduce equivocality (Siraj & Fayek, 2019). Thus, project risk management literature was reviewed in detail to classify the risk factors in a structured manner (Al-Bahar & Crandall, 1990; Boateng et al., 2015; Dikmen, Birgonul, & Han, 2007a; Fang, Li, Fong, & Shen, 2004; Han & Diekmann, 2001; Hastak & Shaked, 2000; Jung & Han, 2017; J. Liu et al., 2016; Sanchez-Cazorla et al., 2016; Tavakolan & Etemadinia, 2017). Consequently, the draft list of the complexity and risk factors was compiled based on the literature review.

In order to test whether the factors in the draft list comply with the actual project management practices and experiences of the practitioners, a brainstorming study was conducted with two experts. Both experts have recently been involved in large-scale construction projects. The first expert, who has 13 years of experience as a risk manager, is responsible for the preparation of risk management plans for industrial projects of an international contractor. The second expert, who works in a multinational energy company, is a senior planning engineer for more than nine years and responsible for integrating project risk management plans into construction schedules. After explaining the aim of the study, the draft list was presented to the experts so that they can help finalize the complexity and risk factors. As a result of the brainstorming session that took around two hours, the complexity and risk factors suitable to the context of mega construction projects were determined.

Settling the complexity factors to be used in the study constituted the most important part of the brainstorming session. Since incorporating all of the 50 factors in the TOE framework into the interview protocol would not be practical, the number of factors was reduced by identifying the most relevant items for mega construction projects. As a result, six technical, seven organizational, and four environmental complexity factors listed in Table 3.1 were determined.

Table 3.1. Complexity Factors in Mega Construction Projects

ID	Complexity Factor	TOE Category
C1	Size of the project	Organizational
C2	Strategic importance of the project	Environmental
C3	Political or macroeconomic instability	Environmental
C4	Variety of financial institutions or sponsors	Organizational
C5	Interactions between the stakeholders	Environmental
C6	Inadequacy of the contract	Organizational
C7	Lack of technical experience	Technical
C8	Changes in the project scope	Technical
C9	Unrealistic project targets	Technical
C10	Unavailability of resources (labor, material, equipment)	Organizational
C11	Interactions between the project disciplines	Organizational
C12	Cultural diversity	Organizational
C13	Multiple critical paths (parallel activities)	Technical
C14	Staff and equipment mobility	Organizational
C15	Physical and logistic constraints	Environmental
C16	Technological novelty of the project	Technical
C17	Originality of the project design	Technical

On the other hand, the experts were largely agreed with the relevance of the risk factors determined in the draft list. After some minor changes, eight factors listed in Table 3.2 were identified as the risks related to mega construction projects.

Table 3.2. Risk Factors in Mega Construction Projects

ID	Risk Factor
R1	Country-Related Political and Economic
R2	Financial
R3	Contractual
R4	Owner-Related
R5	Procurement
R6	Project Management and Organization
R7	Construction-Related/Technological
R8	Design

3.1.1.2 Sampling Procedure

The sampling approach of this research was inspired by the study of Cicmil et al. (2006) that called for a shift to the praxis-based theory building through "project actuality research." This research approach benefits from the lived experience of the practitioners to reflect the empirical reality of the projects. According to Sanchez-Cazorla et al. (2016), the empirical studies based on surveys and detailed interviews with managers are short in supply in the megaproject research. Thus, managers of mega construction projects performed by Turkish contractors over the last two decades were selected as the target population of this study. First of all, mega construction projects that comply with this criterion were explored using public documents, press releases, company reports, and other internet sources. This process resulted in the identification of 50 candidate projects. Then, 32 companies involved in the construction process of these projects as the main contractor, subcontractor, or joint-venture partner were contacted by email. After discussions with the responding companies, eight construction companies associated with 11 mega construction projects agreed to provide data for this study. Due to confidentiality agreements, projects examined in this study are encoded with their ID numbers assigned according to the date of the interview. Descriptive information about these projects is given in Table 3.3.

Table 3.3. Mega Construction Projects Examined in the Study

ID	Type	Cost ($ Billion)	Start Year	Status
P1	Power plant	0.782	2016	In progress
P2	Transport infrastructure	1.200	2008	Completed
P3	Hospital	0.600	2015	Completed
P4	Hospital	0.300	2013	In progress
P5	Pipeline	0.413	2016	Completed
P6	Hospital	0.290	2014	In progress
P7	Airport	0.275	2014	Completed
P8	Pipeline	1.788	2002	Completed
P9	Transport infrastructure	3.600	2004	Completed
P10	Transport infrastructure	7.500	2013	Completed
P11	Power plant	0.632	2014	Completed

While selecting the megaprojects, the main criterion was the cost of the project. The cost thresholds of the selected projects were greater than 0.02% of GDP, which was suggested by Hu et al. (2015b) in Table 2.3 for European countries. As shown in Table 3.3, the minimum cost figure among the megaprojects was $275 million (P7) as conforming to the selected cost threshold. The total cost of all projects is more than $17 billion. In terms of project types, the data set includes three transport infrastructure projects, three hospitals, two pipelines, two power plants, and one airport. Six projects were undertaken by joint-ventures or consortiums, whereas five projects did not have any partnership agreement. There were three Public-Private Partnership (PPP) projects. The remaining projects had a variety of delivery systems and contract payment types. Most of the projects were completed recently, while three of them were progressing with more than 50% completion rate as of the interview date. Apart from the two power plant projects in Bahrain and Iraq, all projects were held in different locations of Turkey. The average peak number of workers was 4200, which reflects the magnitude of the selected projects. In terms of performance, despite the existence of some successful cases, projects in the data set have similarities with the international megaprojects discussed in Section 2.2.4.1. The average cost overrun was more than 20%, whereas the average delay time was approximately 14 months.

Besides the project selection, there were also criteria used for the participant selection. First, they should have been experienced in mega construction projects. Second, they should have been involved in the management process of the selected project from the beginning as they were expected to explain their initial assumptions and plans, as well as problems experienced in the project. Consequently, 18 managers who meet these criteria participated in the study to share the data of 11 mega construction projects. In some projects, there were two participants, each answering the questions in their area of expertise to provide more reliable information. The participant profile is given in Table 3.4.

Table 3.4. Participant Profile

Profile	**Category**	**Distribution**
Gender	Male	15
	Female	3
Education background	B.Sc.	4
	M.Sc.	13
	Ph.D.	1
Years of experience	6-15 years	7
	16-25 years	7
	26-35 years	4
Megaproject experience	Medium	3
	High	9
	Very high	6

All of the participants have occupied senior management positions in the selected projects, such as general coordinator, project manager, and technical office manager. Their average experience in the construction industry was 20.5 years. They were also requested to evaluate their mega construction project experience during the interviews. As demonstrated in Table 3.4, most of them considered their experience level “high” or “very high.”

In terms of the validity of the sampling, equal sample size was used to ensure consistency in the convergent design selected for this research. In other words, quantitative and qualitative data were supplied by the same 18 participants. Although the equal sample size limits the statistical power of the quantitative analysis, the sample has not been increased since making a statistical inference was not an objective of this study. For the qualitative part, the number of projects investigated was found sufficient to provide an empirical grounding (Brookes & Locatelli, 2015). Moreover, the sample size was within the range of 15 to 20 participants suggested by Collins (2010) for similar studies. More importantly, the number of new items added in the thematic analysis, which will be discussed later, showed a decreasing trend throughout the interviews. The gradual decrease indicated that the sample size is enough to reach the theoretical saturation point, where incremental learning is minimal (Eisenhardt, 1989).

3.1.1.3 Interview Procedure

Before the interviews, a protocol that contains questions related to the complexity and risk factors identified in Section 3.1.1.1 was prepared. In order to validate the types of questions, the numerical scale used for the quantitative part, and general format, the interview protocol was evaluated by the two experts who participated in the brainstorming session for the identification of the factors. Thereafter, interviews with the participants of 11 mega construction projects were initiated as of November 2018 and completed within nine months. Since projects to be discussed were known in advance, some preliminary information was collected using internet sources before each meeting. Moreover, the interview protocol that contains questions, research objectives, and the confidentiality statement was sent to the participants so that they could make the necessary preparations. All interviews were held face-to-face in the offices of the participants, while some of them included site visits as well. The average duration of the meetings was approximately two hours, with a minimum of one and a maximum of four hours. All of the interviews were recorded with the permission of the participants.

The interviews were conducted with the parallel data collection questions to address the same concepts in the quantitative and qualitative parts. For the quantitative part, closed-ended survey questions were asked with a five-point Likert scale ranging from very low to very high. These questions supplied numeric data to quantify the complexity, risk, and their relationship in the investigated megaprojects. In order to improve the reliability of the quantitative results, participants were requested to explain their rationale while answering the survey questions. According to Thamhain (2013), as compared to mail surveys, face-to-face interviews may produce more reliable results since the possibility of misinterpretations is minimized. The qualitative part, on the other hand, was based on semi-structured interviews. Although the main questions were determined in advance, for a better understanding of the topics, some additional questions were asked during the interviews, depending on the answers of the participants. Furthermore, as the preliminary themes in the interview protocol may lead to biased outcomes, the participants were encouraged to talk about other complexity and risk factors they encountered in their projects. The advantage of selecting the semi-structured interviews was that they provided flexibility for participants to explain the topics in the way they prefer. While structured interviews may narrow the answers of the interviewees, unstructured interviews may result in useless data in case of a diversion from the main topic (Green, Kao, & Larsen, 2010).

The interview protocol was composed of seven main parts. At each interview, the same questions were asked in the same order. In the first part, there were personal questions to establish the participant profile shown in Table 3.4. The second part included preliminary questions related to the project, such as contract parties, payment type, and time-cost details. The next part contained questions for the pre-project risk assessment. Participants were requested to explain the risk management process employed in their projects and evaluate the eight risk factors given in Table 3.2 by considering the assumptions and decisions at the beginning of the project. In other words, they were expected to talk about the predictions made at the commencement stage rather than real events that happened during the project. The expected impact of these risk factors was measured on the Likert scale. In the fourth part, open-ended questions were asked about the complexity factors experienced in the project. Before starting this part, the complexity definition of Vidal and Marle (2008), which is given in Section 2.1.1, was shared with the participants. They were requested to consider this definition while evaluating the complexity factors in their projects. Following the discussion of each complexity factor given in Table 3.1, the participants were also asked to rate the magnitude of the related factor on the Likert scale. In the fifth part, participants were asked to compare the relative importance of the 17 complexity factors in terms of their contribution to the overall project complexity by rating them on the Likert scale. Then, in the sixth part, by considering the risk events that happened throughout the project, participants rated the actual impact of the eight risk factors at the end of the project. During the post-project risk assessment, they were also requested to explain the risk events in the project with examples. Finally, the seventh part contained some follow-up questions that pertain to the performance evaluation of the project and the lessons learned about complexity and risk management. These questions served for qualitative data analysis. The interview protocol is provided in Appendix A.

After each interview, initial thoughts about the project were recorded by writing short field memos. These notes helped to categorize the themes during the qualitative analysis. Moreover, secondary data obtained during the interviews, such as presentations, project documents, and risk reports, were considered during the analysis to triangulate the data sources. The data analysis procedure is described in the next section.

3.1.2 Data Analysis

In accordance with the mixed-methods approach, quantitative and qualitative analyses were conducted for the data collected from the interviews. The following sections explain the details of both analyses.

3.1.2.1 Quantitative Data Analysis

As the initial step of the quantitative analysis, survey data acquired from the interviews of 11 mega construction projects were compiled into one database. The data for each project was composed of the magnitude and relative importance scores of the 17 complexity factors, as well as the pre-project and post-project scores of the eight risk factors. Based on this data, numerical analyses were performed to quantify the individual score of each complexity factor, overall complexity score of the projects, rate of change in scores of risk factors, and, consequently, the contribution of complexity factors to the unpredictability of risk factors. For the first calculation, the ratings given by the participants in the fourth and fifth parts of the interviews were utilized. Accordingly, the score of complexity factors in a project was calculated using Equation (3.1).

$$\mathrm{C}_{ik} = \mathrm{M}_{ik} \text{ x } \frac{\mathrm{I}_{ik}}{\sum_{i=1}^{n} \mathrm{I}_{ik}} \tag{3.1}$$

where C_{ik} is the complexity score of factor i at project k; M_{ik} is the magnitude of complexity factor i at project k; I_{ik} is the relative importance of complexity factor i at project k; and n is the number of complexity factors, which is 17 in this study.

Then, the overall complexity score of a project was calculated by summing up the individual complexity scores of the factors, as shown in Equation (3.2).

$$\mathrm{C}_{k} = \sum_{i=1}^{n} \mathrm{C}_{ik} \tag{3.2}$$

where C_{k} is the complexity score of project k.

For the rate of change in scores of risk factors, the percentage difference of pre-project and post-project ratings given by the participants in the third and sixth parts of the interviews were calculated according to Equation (3.3).

$$\Delta R_{jk} = \frac{R_{jk2} - R_{jk1}}{R_{jk1}} \text{ x } 100 \tag{3.3}$$

where ΔR_{jk} is the rate of change in score of risk factor j at project k; R_{jk2} is the post-project score of risk factor j at project k; and R_{jk1} is the pre-project score of risk factor j at project k.

Finally, in order to quantify the relationship between complexity and risk, the potential contribution of complexity factors to the unpredictability of risk factors was assessed. In this regard, a weighted score was calculated by multiplying the score of a complexity factor and the rate of change in a risk factor and then summing up the results for all projects. When this number was divided by the summation of the weighted scores for all complexity factors, the contribution percentage of this complexity factor to the unpredictability of the risk factor can be calculated, as shown in Equation (3.4).

$$CR_{ij} = \frac{\sum_{k=1}^{m} C_{ik}\, \Delta R_{jk}}{\sum_{i=1}^{n} \sum_{k=1}^{m} C_{ik}\, \Delta R_{jk}} \text{ x } 100 \tag{3.4}$$

where CR_{ij} is the contribution percentage of complexity factor i to the unpredictability of risk factor j; and m is the number of projects, which is 11 in this study.

Consequently, using Equations (3.1) - (3.4), complexity and risk data of 11 mega construction projects were analyzed to explain the relationship between complexity and risk in numerical terms.

3.1.2.2 Qualitative Data Analysis

For the qualitative data analysis, the grounded theory approach (Corbin & Strauss, 1990) was utilized to build a data-driven framework. The grounded theory is based on deducting the concepts and conceptual relationships from the empirical evidence instead of testing the hypotheses developed from the existing theories. By following this approach, it was intended to propound a framework, which can conceptualize the interactions between complexity and risk. In qualitative research, the conceptual frameworks have been used for both theory building and explaining the relationships observed for a phenomenon (Meredith, 1993). According to Rocco and Plakhotnik (2009), the inclusion of conceptual frameworks in the empirical studies helps to describe the relevant concepts, as well as map their relationship. Therefore, utilizing the explanatory power of a conceptual framework suits the purpose of this study.

In this direction, the audio-recorded interviews belong to 11 projects were transcribed verbatim as the first step of the qualitative data analysis. Although the interviews, and thus transcriptions were in Turkish, examples used in this study were translated into English. Then, the thematic analysis approach of Braun and Clarke (2006) was utilized to code the main themes in the text data. The coding process enables to turn qualitative data into a well-organized and manageable information source to draw a conclusion (Yim, Castaneda, Doolen, Tumer, & Malak, 2015). Accordingly, a coding structure was created to categorize the critical project events, identify the commonalities between the projects, and highlight the essential quotations. Keeping the text transcriptions on MS Excel facilitated the filtering of projects and codes. A text coding applied in this study is exemplified in Figure 3.2.

Person	Text Transcription	Coding	Project
HE:	Do you think the complexity factors that we discussed increase the risks in the project?		P1
TS:	Yes, I think so.		P1
HE:	Can you give a specific example?		P1
TS:	As I mentioned earlier, we knew that we are going to work in a congested construction site from day one. We were also aware that it might cause some risks. However, the impact was more significant than we thought due to some other risks. For example, we experienced some delays caused by economic problems throughout the project. Even though we tried to accelerate the works, it was not effective due to physical constraints.	Macroeconomic Impacts	P1
		Physical / Logistic Constraints	P1
		Time Pressure	P1
GD:	We used more crews that work at the same time to catch up on the schedule.	Time Pressure	P1
TS:	We worked with five subcontractors at the same place, although there should have been two subcontractors. The efficiency was reduced considerably by the physical constraints. In short, there was a chain effect.	Physical / Logistic Constraints	P1
HE:	So, you think that complexity increases the risk?		P1
TS:	Yes, it increases both the number and the impact.	Complexity & Risk Relationship	P1

Figure 3.2. Text Coding Example

The coding process was repeated for the interview data of all projects and, consequently, 91 themes relevant to the complexity and risk were identified. After the first three interviews, the number of new themes coded has decreased considerably. Table 3.5 shows the number of themes identified in each interview.

Table 3.5. Number of Themes Identified in the Coding Process

Project	Total Number of Themes	Number of New Themes
P1	30	30
P2	23	10
P3	37	17
P4	21	6
P5	34	4
P6	22	6
P7	31	4
P8	29	3
P9	28	5
P10	18	4
P11	25	2

As a result, after several iterations with the main themes explaining the relationship between complexity and risk, a conceptual framework including the concepts of risk, uncertainty, complexity, and management strategies was built.

3.1.3 Integration Procedure for a Conceptual Risk Assessment Model

The last step of the mixed-methods approach employed in the first phase was integration. In a convergent design, integration implies the merging of the quantitative and qualitative analysis by relating their findings. The aim of the integration is developing a more comprehensive understanding than provided by either type of data separately (Creswell & Plano Clark, 2017). Moreover, it serves to improve the internal validity of the research by triangulating two different data sets (Bryman, 2006).

In this research, the integration was achieved by merging and interpreting the findings from the quantitative and qualitative analysis. While the quantitative results served to verify the existence of complexity and risk relationship in numerical terms, the qualitative results enabled to explain the nature of this relationship with a conceptual framework. The integration procedure, on the other hand, provided insights into the implications of this relationship for risk management.

The quantitative findings, which will be presented in Section 4.1, revealed that there might be a correlation between complexity and risk scores. This result suggested incorporating complexity factors into the risk assessment process to quantify their impact. Furthermore, the qualitative findings, which will be presented in Section 4.2, demonstrated the conceptual links between risk, uncertainty, complexity, and management strategies. These concepts and their interactions should also be taken into account during the risk assessment process to quantify the risks of mega construction projects more realistically. Correspondingly, by integrating the findings of the quantitative and qualitative analysis, a novel conceptual model, entitled Integrated Risk Assessment Process (IRAP), was proposed to address the relationships among the risk-related concepts during the risk assessment process. Details of IRAP, together with the other findings of the first phase, will be discussed in Chapter 4. The next section elaborates on the analytical model developed based on the conceptual model.

3.2 Phase 2: Analytical Risk Quantification Model

The second phase of the research includes studies carried out to operationalize the risk assessment process proposed in the first phase via an analytical model. As it will be detailed in Chapter 4, findings from the first phase served to discover the network structure among the risk-related concepts. For this reason, developing a network-based analytical model aligns with the risk assessment approach proposed in this study. In this respect, an ANP model was proposed to interconnect the risk-related concepts during the risk assessment process. ANP is a generalized form of the Analytic Hierarchy Process (AHP), which is used in multi-criteria decision-making problems. Both methods were devised by Thomas L. Saaty. While AHP is useful for hierarchical decision-making problems, ANP can model network structures as well (Saaty, 2005). Therefore, it has been applied to various decision-making problems in the project management domain, such as contractor selection (Cheng & Li, 2004; El-Abbasy, Zayed, Ahmed, Alzraiee, & Abouhamad, 2013), project selection (Dikmen, Birgonul, & Ozorhon, 2007b; Grady, He, & Peeta, 2015), performance evaluation (Ozorhon, Dikmen, & Birgonul, 2007; Tohumcu & Karasakal, 2010), stakeholder evaluation (Aragonés-Beltrán, García-Melón, & Montesinos-Valera, 2017; Wang, Li, & Fang, 2018), and risk prioritization (Boateng et al., 2015; Hatefi & Tamošaitienė, 2019).

Both AHP and ANP methods require pairwise comparisons to establish the relative importance of the components in the decision-making model (Saaty & Vargas, 2013). Hence, after the model development, components should be rated by comparing them with each other. The rating process is usually performed by a group of experts (Saaty, 2005). Using the geometric mean of the questionnaire data or conducting a Delphi process are convenient ways of expert knowledge elicitation in ANP studies (Kheybari, Rezaie, & Farazmand, 2020). In this study, the latter was adopted to build an analytical model with the consensus of the experts. Delphi method is a flexible way of collecting expert opinions through successive rounds of questionnaires and feedback (Vidal et al., 2011). For this reason, it has been frequently used in ANP-based complexity or risk research (Afzal, Yunfei, Sajid, & Afzal, 2020; Bu-Qammaz, Dikmen, & Birgonul, 2009; Dikmen, Birgonul, Ozorhon, & Egilmezer Sapci, 2010; He et al., 2015; Karamoozian, Wu, Chen, & Luo, 2019; Valipour et al., 2015).

The studies conducted in the second phase were launched by linking the themes of the conceptual risk assessment model over an ANP model. Then, based on this model, a two-round Delphi study was conducted with five experts. In the first round, pairwise comparisons of the experts were acquired separately through questionnaires on a spreadsheet-based data collection tool. In the second round, a panel was organized to reach a consensus among the experts. By using consolidated results, the ANP calculations were made to obtain weighted parameters for risk quantification. The procedure used in these studies is explained in the following sections.

3.2.1 Development of the ANP Model

As the analytical model serves to operationalize the conceptual model, the ANP model was built by linking the four themes included in IRAP. Accordingly, risk, uncertainty, complexity, and management strategies constituted the main components of the ANP model. The complexity and risk parameters in the model comprised the factors listed in Table 3.1 and Table 3.2, respectively. On the other hand, two sub-categories were defined for each of the uncertainty and management strategies parameters. Based on the links between these parameters, 122 pairwise comparisons that constituted 34 comparison matrices under 11 comparison sets were identified. The details of the ANP model will be presented in Section 5.1.

3.2.2 Delphi Study

For the pairwise comparisons identified in the ANP model, a two-round Delphi study was conducted with five domain experts. According to the bibliographic analysis carried out by Ameyaw, Hu, Shan, Chan, and Le (2016) for applications of the Delphi method in construction engineering and management research, the number of experts in Delphi studies ranged from three to 93. Although using a high number of experts is suitable for studies based on surveys only, it may be inconvenient for the expert panels (Li, Han, Luo, & Zhang, 2019). Moreover, the qualifications of the experts are more important than their numbers in Delphi studies (Dikmen et al., 2010). Therefore, benefiting from the experience of five experts was considered appropriate for this study. The expert group was composed of three industry practitioners and two academicians. While the industry practitioners had expertise in preparing risk management plans for large-scale construction projects, academicians, who published many research papers on risk-related concepts, were highly experienced in project risk management. Owing to their experience and knowledge, the pairwise comparisons elicited from these experts are believed to be reliable for determining the weights of the ANP model. Brief information about the experts is provided in Table 3.6.

Table 3.6. Expert Profile of the Delphi Study

Expert	**Position**	**Years of Experience**	**Education Background**
Expert A	Risk Management Consultant	8	M.Sc.
Expert B	Lead Project Management Specialist	10	M.Sc.
Expert C	Assistant Professor	15	Ph.D.
Expert D	Professor	26	Ph.D.
Expert E	Senior Project Manager	28	M.Sc.

In the first round of the Delphi study, an interactive questionnaire that contains the 122 pairwise comparisons in the ANP model was shared with five experts separately.

The experts answered the questions via a spreadsheet-based data collection tool developed to facilitate the comparison procedure. The tool was capable of performing the ANP calculations as well. Implementing the ANP studies with standard questionnaire forms could be a tedious process. Furthermore, they lack a feedback mechanism to warn the respondents against the inconsistency in the pairwise comparisons, which will be discussed in the next section. On the other hand, despite the existence of commercial ANP software, such as Super Decisions, Expert Choice, and Decision Lens, they may not be accessible or applicable to experts. The tool developed in MS Excel could be practically used without any requirement for prior knowledge. Moreover, it specifically designed for this study to inform the experts about the ANP model and guide them for the pairwise comparisons. The index page of the tool involved general explanations about the ANP model and links to the 11 comparison sets. Moreover, experts were provided with more detailed information about the operations they are required to perform on the page of each comparison set. Consequently, the first round was concluded by collecting the questionnaires answered by the experts in the data collection tool.

In the second round of the Delphi study, an online panel was conducted with the experts who participated in the first round. Prior to the meeting, all pairwise comparisons made in the first round were shared with the experts to provide information about the other selections. The aim of the panel was to build a consensus among the participants. In particular, they were expected to reach an agreement on the comparisons selected differently in the first round. The data collection tool was also utilized during the discussions to check the consistency of the alternative selections. As a result of the expert panel that took approximately two hours, the pairwise comparisons of the experts were refined in a consistent manner. The consolidated comparisons served to calculate the weights of the parameters in the ANP model for risk quantification. The following section explains the theoretical background of all ANP calculations in the second phase, together with the examples from the data collection tool.

3.2.3 ANP Calculations

The first step of the ANP calculations is the pairwise comparisons of the components in the model. Then, the priorities of the components are calculated based on these comparisons. After verifying the consistency of the comparisons, priority weights are obtained with supermatrix calculations. The subsequent sections present the details of these calculations.

3.2.3.1 Pairwise Comparisons

In all AHP and ANP models, pairwise comparisons are necessary to determine how many times more dominant is the given component than the compared component with respect to a certain criterion or attribute, which is usually called the "control criterion" (Saaty, 2005; Saaty & Vargas, 2013). The relative importance of the components is measured based on Saaty's nine-point scale. In this scale, "1" indicates equal importance, whereas "9" shows that one of the alternatives is extremely more important than the other. The scale used for pairwise comparisons is presented in Table 3.7.

Table 3.7. The Fundamental Scale of Absolute Numbers for Pairwise Comparisons (adapted from Saaty, 2005)

Intensity of Importance	**Definition**
1	Equal importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance

Accordingly, an expert has three possible options for the pairwise comparisons: Selecting the first alternative, selecting the second alternative, and considering them equally important. While the last option automatically takes the value of "1," the other options have to be rated according to the scale given in Table 3.7. In this study, the data collection tool was designed to assist the experts in making these selections for each comparison set. Figure 3.3 exemplifies the pairwise comparisons in one of these sets.

Pairwise Comparison of Environmental Factors with respect to Environmental Complexity

In this set, you are asked to compare the four environmental complexity factors based on their contribution to the environmental complexity. For each comparison alternative, please answer the questions in cells C4 and D4. You will see the priority weights (B13:B16) of each environmental complexity factor when you complete the selections. If you get a warning about the consistency ratio (B17), please reconsider your comparisons. **Environmental Complexity Factors:**
C2: Strategic importance of the project, **C3:** Political or macroeconomic instability, **C5:** Interactions between the stakeholders, **C15:** Physical and logistic constraints

Compared Alternatives		Among the alternatives compared, which one has a more significant contribution to the environmental complexity?	How much more significant is the alternative you have selected when compared to the other? (**1**: Equally, **2**: Equally to Moderately, **3**: Moderately, **4**: Moderately to Strongly, **5**: Strongly, **6**: Strongly to Very Strongly, **7**: Very Strongly, **8**: Very Strongly to Extremely, **9**: Extremely)
C2	C3	Equal	1
C2	C5	C5	4
C2	C15	C2	5
C3	C5	C5	3
C3	C15	C3	6
C5	C15	Please select	Please select

C5
C15
Equal

2
3
4
5
6
7
8
9

Figure 3.3. Pairwise Comparison Example in the Data Collection Tool

The data collection tool was also capable of alerting experts in case of an invalid selection. As illustrated in Figure 3.4, the rating of a pairwise comparison must be "1" if the alternatives are selected as equally important. Similarly, the rating cannot be "1" if the alternatives are not equally important.

Among the alternatives compared, which one has a more significant contribution to the environmental complexity?	How much more significant is the alternative you have selected when compared to the other? (**1**: Equally, **2**: Equally to Moderately, **3**: Moderately, **4**: Moderately to Strongly, **5**: Strongly, **6**: Strongly to Very Strongly, **7**: Very Strongly, **8**: Very Strongly to Extremely, **9**: Extremely)	
Equal	1	
C5	4	
Equal	5	Error: Selected value must be '1' if the alternatives have EQUAL significance
C5	3	
C3	1	Error: Selected value cannot be '1' if the alternatives do not have EQUAL significance
C5	9	

Figure 3.4. Warnings Shown by the Data Collection Tool for Invalid Selections

3.2.3.2 Calculation of the Priorities

In AHP and ANP applications, priorities of the compared alternatives are calculated over the comparison matrices derived from the pairwise comparisons (Saaty, 2005). For instance, Table 3.8 shows the comparison matrix derived from the pairwise comparisons in Figure 3.3.

Table 3.8. Comparison Matrix Example

Factors	**C2**	**C3**	**C5**	**C15**
C2	**1**	1	1/4	5
C3	1	**1**	1/3	6
C5	4	3	**1**	9
C15	1/5	1/6	1/9	**1**

As shown in Table 3.8, values in the diagonal of the comparison matrices are always one, which implies that an element cannot be more or less important than itself. Another important aspect of the comparison matrices is the "reciprocal property" (Saaty & Vargas, 2013). For example, if C5 is determined to be "4" times more important than C2, then the inverse comparison is assigned the reciprocal value of "1/4".

In the next step, the priorities of the elements that constitute the comparison matrix are calculated by the eigenvalue method (Saaty & Vargas, 2013). Accordingly, the priorities vector is obtained with matrix algebra, as shown in Equation (3.5).

$$\widehat{\mathrm{A}} \cdot \vec{\mathrm{p}} = \lambda_{\max} \cdot \vec{\mathrm{p}} \tag{3.5}$$

where $\widehat{\mathrm{A}}$ is the comparison matrix; $\lambda_{\max}$ is the principal eigenvalue of the matrix $\widehat{\mathrm{A}}$; and $\vec{\mathrm{p}}$ is the priorities vector.

Although there are different methods to derive priorities, such as the left eigenvalue, the geometric mean (logarithmic least squares), and the mean of the normalized values (Ishizaka & Lusti, 2006), the data collection tool stuck to the principal right eigenvector approach of Saaty (2005). To illustrate the calculation of the priorities vector by the tool, Figure 3.5 demonstrates the priorities obtained from the comparison matrix given in Table 3.8.

Results	
C2	18.369%
C3	20.596%
C5	56.680%
C15	4.355%
Consistency Ratio	0.02920

Return to the Index page

Return to the previous comparison

Go to the next comparison

Figure 3.5. Calculation of the Priorities in the Data Collection Tool

3.2.3.3 Calculation of the Consistency Ratio

Consistency of the comparison matrices is another important aspect regarding the pairwise comparisons. In order to achieve a higher degree of reliability in the model, the selections of the expert must be consistent enough. For instance, if Alternative A was considered more important than Alternative B and Alternative B was considered more important than Alternative C, then selecting Alternative C more important than Alternative A would increase the inconsistency of the comparison matrix. Although there is some allowance for non-linear relationships, the consistency ratio of a comparison matrix should remain within a certain limit (Saaty, 2005).

The first step of determining the consistency ratio is calculating the consistency index according to Equation (3.6).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.6}$$

where CI is the consistency index; λ_{max} is the principal eigenvalue of the comparison matrix; and n is the size of the square comparison matrix.

Then, the consistency ratio is calculated by dividing the consistency index to the corresponding random index value, as shown in Equation (3.7).

$$CR = \frac{CI}{RI} \tag{3.7}$$

where CR is the consistency ratio; and RI is the value of the random index.

The random index is composed of the experimental values proposed by Saaty (1980) for different matrix sizes. These values are given in Table 3.9.

Table 3.9. Random Index Values
(adapted from Saaty, 2005)

Size of the Matrix (n)	**Random Index Value**
1	-
2	-
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.40
9	1.45
10	1.49

The data collection tool was also capable of calculating the consistency ratio, as illustrated previously in Figure 3.5. For a perfectly consistent comparison matrix, the consistency ratio calculated by Equations (3.6 and 3.7) should be 0. The recommended maximum value of the consistency ratio is 0.1 (Saaty, 2005). Based on this number, the data collection tool was checking whether the comparison matrix is consistent or not. In case the pairwise comparisons result in a consistency ratio greater than 0.1, the tool provided instant feedback for experts to reconsider their selections, as exemplified in Figure 3.6.

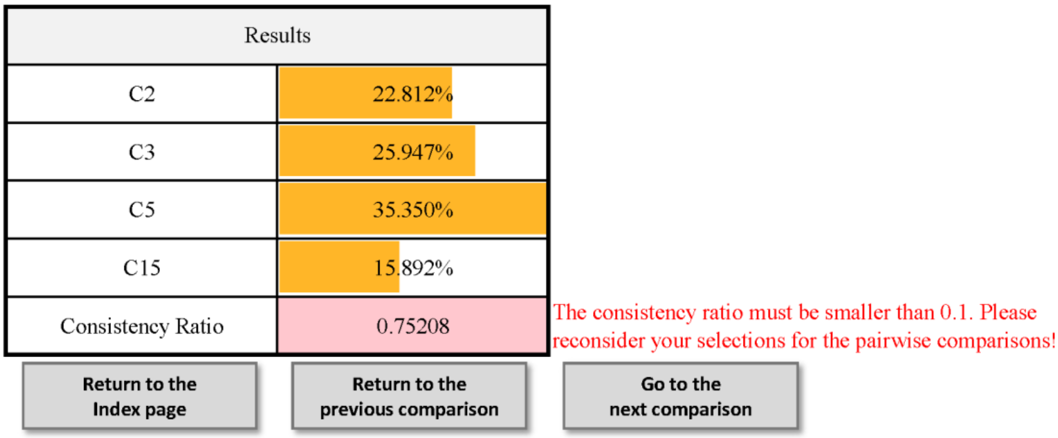


Figure 3.6. Feedback Given by the Data Collection Tool for the Consistency Ratio

3.2.3.4 Supermatrix Calculations

The priority weights of the components in an ANP model are obtained through three-step supermatrix calculations. A supermatrix is a two-dimensional matrix constructed by bringing the elements of different matrices together (Saaty, 2005). In this respect, the first step is constructing the unweighted supermatrix by placing priorities vectors derived from the comparison matrices in the appropriate columns. This process serves to get global priorities through a single supermatrix by gathering the local priorities from the comparison matrices. The values in the supermatrix show the influence of the components on each other. Zero indicates that there is not any relationship between the corresponding row and column elements (Saaty, 2005). The second step is converting the unweighted supermatrix into a weighted supermatrix by multiplying its values with the corresponding cluster weights. The cluster weights are determined by the pairwise comparisons of the related clusters. The aim of the second step is obtaining a column stochastic matrix, where values at each column add up to one (Saaty & Vargas, 2013). Finally, the weighted supermatrix is transformed into a limit supermatrix in the third step. For this purpose, the weighted supermatrix is raised to powers until all columns are stabilized (Saaty & Vargas, 2013). The resulting matrix yields the relative importance weights for every component in the ANP model.

In this study, the ANP calculations described above were made for the pairwise comparisons obtained from the Delphi study. With the priorities vectors generated by the data collection tool, the supermatrices were constructed to calculate the weighted parameters for risk quantification. Details of the calculations related to the analytical model, together with the other findings of the second phase, will be discussed in Chapter 5. The next section covers the details of the validation studies for the proposed risk assessment approach.

3.3 Phase 3: Validation of the Proposed Risk Assessment Approach

The third phase of the research contains testing and validation studies. Validation of the research methodology and its results is an essential part of scientific study (Lucko & Rojas, 2010). In this regard, a comprehensive validation scheme was designed to test both the risk quantification performance of the analytical model and the applicability of the proposed risk assessment process in general. The subsequent sections summarize the studies carried out in this context.

3.3.1 Testing the Risk Quantification Performance

As an initial step of the validation studies, the risk quantification performance of the ANP model was tested with the data of 11 mega construction projects examined in the first phase of the research. Verifying the model performance with real project data is a reasonable approach in ANP studies (Bu-Qammaz et al., 2009; Erdem & Ozorhon, 2015).

The ANP model developed in this study calculates the overall risk of a mega construction project over eight risk factors whose scores are procured by rating the 17 complexity factors and two uncertainty categories. In other words, complexity and uncertainty constitute the input parameters, whereas risk is the output parameter. In order to test the risk quantification performance of the model, the real data of complexity and uncertainty should be fed into the model, and the risk score calculated by the model should be compared with the actual risk data. For this purpose, data of 11 megaprojects obtained through the interviews with 18 managers were utilized. Post-project risk ratings given by the participants for eight factors were considered actual risk data. Moreover, scores calculated by Equation (3.1) were used as actual complexity data of 17 factors. However, to ensure consistency with the risk ratings, complexity scores calculated by Equation (3.1) were normalized such that the maximum score would be five. On the other hand, the actual uncertainty data that constitute the other input parameter of the model were not available since the interviews did not include the numerical questions related to the two uncertainty types. For this reason, participants were contacted again to request ratings of the two uncertainty categories on a five-point Likert scale as well as the approval of the initial complexity and risk scores.

At the end of this process, scores available for 17 complexity factors and two uncertainty categories were multiplied with the corresponding weights of the ANP model to estimate the scores of eight risk factors at each project. Then, the percentage error of the model in predicting the risk score of each factor was calculated based on the average values obtained from 11 projects, as shown in Equation (3.8).

$$\mathrm{RSPE}_j = \frac{\frac{1}{m}\sum_{k=1}^{m} \mathrm{RA}_{jk} - \frac{1}{m}\sum_{k=1}^{m} \mathrm{RE}_{jk}}{\frac{1}{m}\sum_{k=1}^{m} \mathrm{RA}_{jk}} \times 100 \qquad (3.8)$$

where RSPE_j is the percentage error of the model in predicting the score of risk factor j; RA_{jk} is the actual score of risk factor j at project k obtained by the post-project assessment; RE_{jk} is the score of risk factor j at project k estimated by the model; and m is the number of projects, which is 11 in this study.

Besides the individual factors, the performance of the model in predicting the overall project risk score was also evaluated. For this purpose, the overall risk score of each project was calculated by taking the weighted average of the post-project risk ratings for eight factors. Weights were provided by the ANP model so that comparisons can be consistent. Then, the overall risk scores of 11 projects were estimated by the model. Based on these results, the percentage error of the model in predicting the overall project risk score was calculated according to Equation (3.9).

$$\text{MAPE} = \frac{1}{m}\sum_{k=1}^{m}\left|\frac{\text{ORA}_k \text{ - ORE}_k}{\text{ORA}_k}\right| \text{ x } 100 \tag{3.9}$$

where MAPE is the mean absolute percentage error of the model in predicting the overall risk score of 11 projects; ORA_k is the actual overall risk score of project *k* obtained by the post-project assessment; and ORE_k is the overall risk score of project *k* estimated by the model.

Consequently, calculations performed with Equations (3.8 and 3.9) enabled to test the accuracy of the ANP model. The results of these calculations will be discussed in Chapter 6.

3.3.2 Testing the Applicability

After verifying the potential of the analytical model in terms of predicting the risk scores, the applicability of the entire risk assessment process in practice was tested with a real megaproject in the second step of the validation studies. Validating a research study with an in-depth analysis of a single case has frequently been practiced in the field of project management (He et al., 2015; Koppenjan et al., 2011).

Accordingly, a demonstrative case study was conducted with the retrospective analysis of a mega pipeline project investigated in the first phase of the research. The details of the project were provided by the planning and contracts manager, who has 15 years of experience in large-scale construction projects. Due to the broad authority and responsibility he owned in the project, all managerial and technical issues could be elucidated. During the case analysis, IRAP was applied to three stages of the project. In this respect, complexity and uncertainty factors, as well as strategies implemented to manage them, were analyzed at the beginning, middle, and end of the project. Then, the ANP model was employed to calculate the risk scores of the project at these three stages over the identified complexity and uncertainty factors. Furthermore, in order to clarify the role of management strategies in the assessment process, risks at the planning stage of the project were calculated without considering the strategies implemented for complexity and uncertainty factors. With the rating exercise, the variation of the complexity, uncertainty, and risk levels in the project was observed.

As a result, the potential contributions of the proposed risk assessment approach to risk management and monitoring in mega construction projects were evaluated with a real application. The findings from the demonstrative case study will be discussed in Chapter 6.

3.4 Concluding Remarks

As a summary, the research design presented in Figure 3.1 has been applied in three phases. The studies in the first phase cover the development of a conceptual model to incorporate complexity into the risk assessment process. The second phase explains the operationalization of the conceptual model through an analytical model. Finally, the third phase includes studies conducted to ensure the validity of the proposed risk assessment approach. The findings from each phase of the research will be discussed in the next three chapters.

CHAPTER 4

A CONCEPTUAL MODEL FOR INTEGRATED RISK ASSESSMENT

This chapter elaborates on the results from the first phase of the research. The following sections present the quantitative and qualitative findings of the mixed-methods approach, as well as their integration to build a conceptual model that incorporates complexity into the risk assessment process in mega construction projects.

4.1 Quantitative Findings

The quantitative findings of the study are based on the data analysis procedure explained in Section 3.1.2.1. The subsequent sections report and discuss the complexity scores, pre-project and post-project risk assessment scores, and quantification of complexity and risk relationship in 11 mega construction projects.

4.1.1 Complexity Scores

The mega construction projects investigated in this study have been exposed to different complexity levels. For 17 factors assessed in these projects, the complexity scores were calculated using Equation (3.1). Then, according to Equation (3.2), the individual complexity scores were summed to determine the total complexity score of each project. Figure 4.1 presents the intra-project and inter-project comparison of complexity factors, together with the project complexity scores at the bottom part.

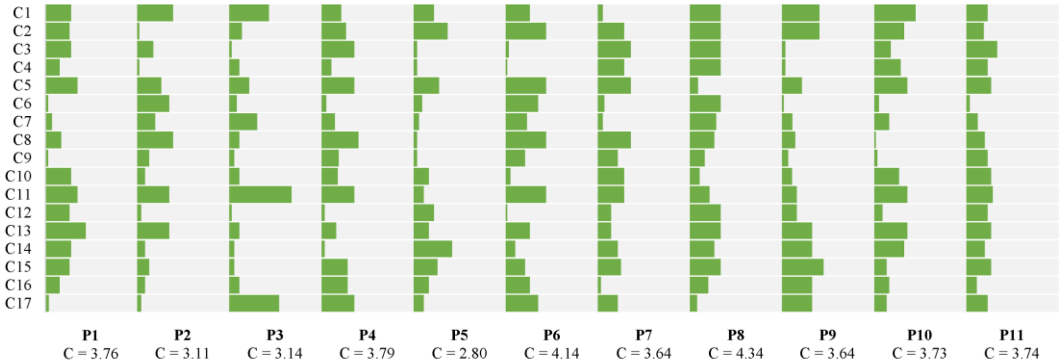


Figure 4.1. Results of the Project Complexity Analysis
(adapted from Erol, Dikmen, Atasoy, & Birgonul, 2020)

In addition to complexity levels shown separately in the projects, the average complexity scores of 17 factors in 11 projects are given in Table 4.1.

Table 4.1. Average Complexity Scores in 11 Mega Construction Projects

ID	**Complexity Score**
C1	0.30
C2	0.28
C3	0.20
C4	0.15
C5	0.29
C6	0.13
C7	0.16
C8	0.23
C9	0.12
C10	0.17
C11	0.33
C12	0.14
C13	0.27
C14	0.21
C15	0.24
C16	0.17
C17	0.22

According to the average values shown in Table 4.1, interactions between the project disciplines (C11), size of the project (C1), interactions between the stakeholders (C5), strategic importance of the project (C2), and multiple critical paths (parallel activities) (C13) were determined the top five complexity factors in the investigated projects. They represented all three complexity categories of the TOE framework since C11 and C1 are organizational factors, C5 and C2 are environmental factors, and C13 is a technical factor. They were also listed among the top five factors in at least six projects, which corresponds to more than half of the cases. As their names imply, C11 and C5 are the complexity factors pertain to dynamic interactions between the project elements. Interactions were considered among the important drivers of the project complexity by several researchers (Eybpoosh et al., 2011; Luo et al., 2017). The findings of this study supported their opinion. The high level of complexity observed in some factors were more closely associated with the characteristic features of megaprojects discussed in Section 2.2.3. Size and strategic importance are critical attributes that increase the complexity of mega construction projects (Jia et al., 2011a). Hence, C1 and C2 were ranked among the top factors in this study. Moreover, concurrent execution of the activities may be related to time pressure inflicted by the political value or strategic importance of the megaprojects (Capka, 2004). For this reason, C13 was another significant complexity factor among the projects examined in this study.

Besides these factors, two complexity factors worth mentioning are changes in the project scope (C8) and political or macroeconomic instability (C3). Even though C8 did not rank among the top five factors in seven projects, it was the most significant complexity factor in the remaining four projects. This result indicates that scope creep may be a critical complexity source depending on the project context. During the interviews, it was noted that the impact of scope changes was extended, in case the design is prepared by the project owner as well as the communication mechanism among the contractual parties is not working well. C3 was another context-dependent factor. It was the most significant complexity source in three projects and listed among the top five factors in two other projects. Most of the participants mentioned that country-related problems, such as the coup attempt, currency fluctuations, and terrorist actions, affected their projects. For the projects more vulnerable to these problems because of their locations, financial arrangements, or contract conditions, C3 was a critical complexity factor.

On the other hand, unrealistic project targets (C9), inadequacy of the contract (C6), and cultural diversity (C12) were the least significant complexity factors. Despite the performance issues of the projects in the data set, participants did not consider C9 an important complexity source. Similarly, though the role of the contractual functions in project complexity has been emphasized by some researchers (Gao et al., 2018; Szentes & Eriksson, 2016), C6 was not rated as a significant factor in this study. Finally, as cultural issues were found relatively more manageable by the participants of this study, C12 was a less important complexity factor.

4.1.2 Pre-Project and Post-Project Risk Assessment Scores

Pre-project and post-project risk assessment scores revealed the alterations in the impact of risk factors. Figure 4.2 depicts the risk levels determined by the participants at the beginning and end of the 11 projects for eight factors. The average scores of all projects are also plotted on the bottom-right corner.

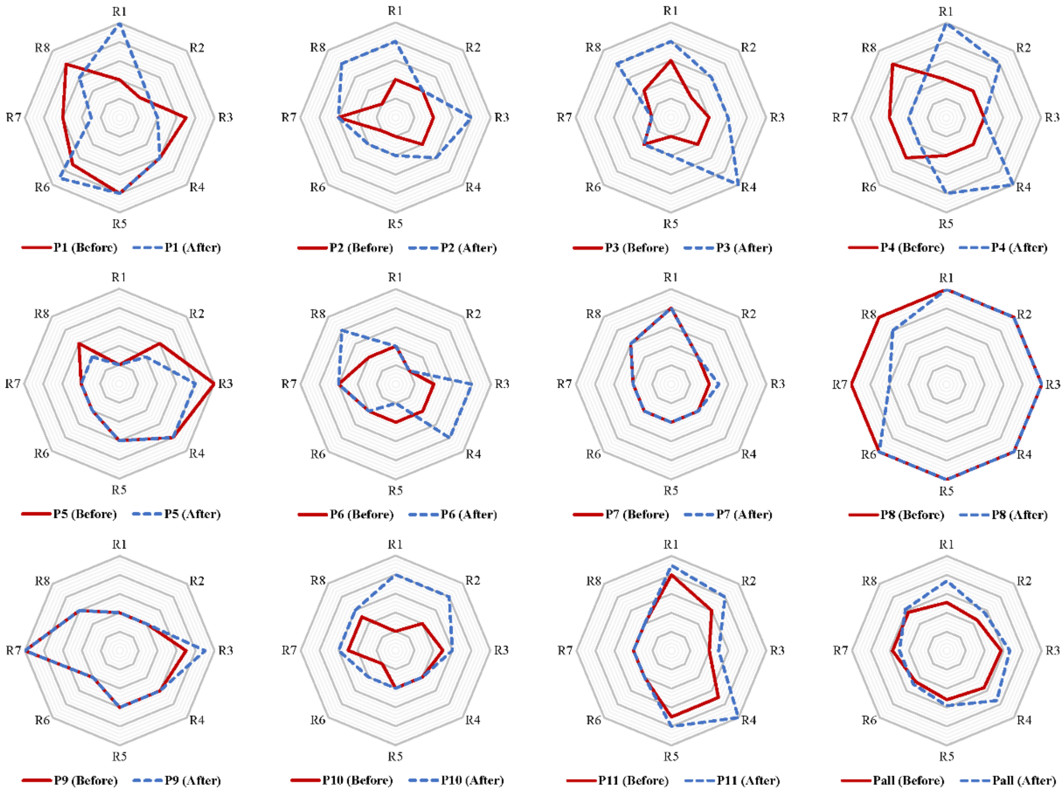


Figure 4.2. Pre-Project and Post-Project Risk Assessments
(adapted from Erol et al., 2020)

Figure 4.2 exhibits that projects have different behavior in terms of the changes in the risk scores. The impact of the many risk factors in P2, P3, P10, and P11 increased, whereas there was a declining trend in P5 and P8. P1, P4, and P6 had both types of risk factors with increasing and decreasing impact scores. On the other hand, risk factors in P7 and P9 remained almost unchanged. Table 4.2 lists the changes in the risk impact scores of 11 projects.

Table 4.2. Changes in the Risk Impact Scores of 11 Mega Construction Projects

ID	Projects having an increased risk impact score	Projects having a decreased risk impact score
R1	P1 – P2 – P3 – P4 – P10 – P11	N/A
R2	P1 – P3 – P4 – P10 – P11	P5
R3	P2 – P3 – P6 – P7 – P9 – P10 – P11	P1 – P5
R4	P2 – P3 – P4 – P6 – P11	N/A
R5	P2 – P3 – P4 – P11	P6
R6	P1 – P2 – P10	P4
R7	P10	P1 – P4 – P8
R8	P2 – P3 – P6 – P10	P1 – P4 – P5 – P8

Besides the risk variations, the average of the pre-project and post-project risk assessment scores in 11 projects, together with the rate of change in the score of each risk factor calculated by Equation (3.3), are given in Table 4.3.

Table 4.3. Average Risk Scores in 11 Mega Construction Projects

ID	Pre-Project Risk Score	Post-Project Risk Score	Rate of Change (%)
R1	2.55	3.68	44.64
R2	2.27	2.82	24.00
R3	2.86	3.32	15.87
R4	2.77	3.73	34.43
R5	2.59	2.91	12.28
R6	2.32	2.50	7.84
R7	2.86	2.50	-12.70
R8	2.86	3.09	7.94

According to the average values given in Table 4.3, except one, post-project scores of all risk factors were greater than the pre-project scores. Country-related political and economic risks (R1) and owner-related risks (R4) were the two factors with the highest rate of change, which implies that predicting their impact could be challenging in mega construction projects. Moreover, their impact scores did not decrease in any of the projects, as shown in Table 4.2. Despite the fact that the rate of change was greater than 10% for financial risks (R2), contractual risks (R3), and procurement risks (R5), their post-project assessment scores were smaller in some of the projects. In terms of predictability, project management and organization risks (R6) and construction-related/technological risks (R7) were considered the most stable factors because their ratings varied only in four projects. In contrast to these factors, predicting the impact of design risks (R8) was more difficult. Even though the average rate of change is not high for this risk factor, it had the same pre-project and post-project scores only in three projects. Thus, the impact of design risks may be higher or lower than expected, depending on the context of the megaproject. Finally, it should be noted that R7 was the only factor with a negative rate of change in the list. This result suggests that managers may overestimate the impact of the technical risks at the beginning of the megaprojects.

4.1.3 Quantification of Complexity and Risk Relationship

The findings presented in Sections 4.1.1 and 4.1.2 handled complexity and risk factors separately. This section, on the other hand, discusses the results by taking their interrelations into account. When the complexity and risk scores of 11 projects are interpreted together, it is deduced that the predictability of risk factors may be different from project to project, regardless of their overall complexity. For this reason, it is necessary to analyze the individual influence of complexity factors on each risk factor to explain the relationship between complexity and risk thoroughly.

Accordingly, projects were grouped based on the change in their pre-project and post-project risk assessment scores, as shown in Table 4.2. Then, the rate of change in the score of each risk factor was calculated for these projects using Equation (3.3). To illustrate this procedure, Figure 4.3 demonstrates the projects grouped per design risks (R8) on a bubble diagram.

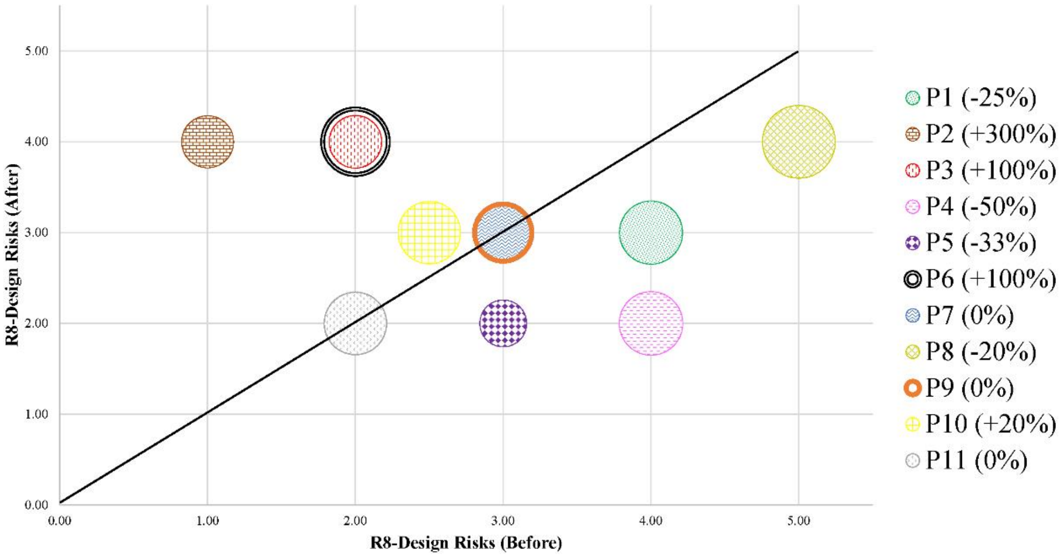


Figure 4.3. Changes in the Design Risks (R8) of 11 Mega Construction Projects

In Figure 4.3, the x-axis and y-axis show the pre-project and post-project risk scores, respectively. Therefore, the post-project score of a project under the diagonal line was smaller than its pre-project score, whereas a project above the line had an increased risk impact score. The risk of the projects on the line remained unchanged. The legend in the right-most part displays the rate of change in the risk score of each project. The bubble size, on the other hand, indicates the total complexity score of the projects. The rate of change calculated for each project was multiplied with the scores of 17 complexity factors in these projects. Then, the results obtained from all projects were summed to calculate a weighted score for each complexity factor. Finally, according to Equation (3.4), the weighted score of a complexity factor was divided by the summation of all weighted scores to calculate the contribution percentage of this complexity factor to the unpredictability of the risk factor. Table 4.4 exemplifies the impact of the complexity factors on R8 with the weighted scores and contribution percentages.

Table 4.4. Impact of the Complexity Factors on the Design Risks (R8)

ID	Weighted Score	Contribution to the Unpredictability (%)
C1	1.6	12.7
C2	0.3	2.4
C3	0.3	2.4
C4	0.1	0.8
C5	1.1	8.7
C6	1.3	10.3
C7	1.0	7.9
C8	1.4	11.1
C9	0.5	4.0
C10	0.2	1.6
C11	1.9	15.1
C12	0.0	0.0
C13	1.2	9.5
C14	0.2	1.6
C15	0.3	2.4
C16	0.4	3.2
C17	0.8	6.3

According to the results given in Table 4.4, interactions between the project disciplines (C11), size of the project (C1), changes in the project scope (C8), inadequacy of the contract (C6), and multiple critical paths (parallel activities) (C13) were more closely associated with the unpredictability of the risks related to the project design. All of these factors belong to technical and organizational categories.

The procedure described above was repeated for all risk factors to identify the possible interactions between complexity and risk. In order to simplify the overall picture, the average values of the weighted scores were determined for technical, organizational, and environmental factors, and the contribution percentages were calculated over these category values. Table 4.5 presents the contribution percentage of each complexity category to the unpredictability of risk factors.

Table 4.5. Contribution of Complexity Categories to the Unpredictability of Risks

ID	Technical Complexity (%)	Organizational Complexity (%)	Environmental Complexity (%)
R1	27.65	33.73	38.62
R2	31.70	32.37	35.93
R3	38.09	29.71	32.20
R4	36.86	28.20	34.94
R5	36.22	32.37	31.41
R6	26.37	41.09	32.54
R7	29.43	29.47	41.10
R8	40.73	35.45	23.82

The percentages calculated in Table 4.5 reveal that each complexity category had the most significant impact on the unpredictability of at least one risk factor. Firstly, environmental complexity had the highest contribution percentage to country-related political and economic risks (R1) and financial risks (R2). These results provide useful insights into the relationship between environmental complexity and external risks that stem from political, economic, and financial factors. Variations in the impact scores of contractual risks (R3), owner-related risks (R4), and procurement risks (R5) were mainly associated with technical complexity. Even though technical complexity did not receive as much attention as organizational complexity in some studies (Qureshi & Kang, 2015; Vidal & Marle, 2008), the findings of this research suggest that technical factors may be significant for mega construction projects. Nonetheless, organizational complexity, too, had important contributions to the unpredictability of some risk factors. As expected, it had the highest proportion in project management and organization risks (R6), which implies that it could be more challenging for megaproject managers to predict the impact of the managerial and organizational risks under high organizational complexity. As discussed in Section 4.1.2, construction-related/technological risks (R7) was the only factor whose average rate of change is negative. Thus, the results given in Table 4.5 can be interpreted that limiting the technical as well as organizational complexity may facilitate predicting the impact of the technical risks. Finally, change in design risks (R8) was mainly attributed to high technical complexity. However, the role of organizational complexity should not be underestimated. As shown in Table 4.4, the contribution of the organizational complexity factors, such as C1, C6, and C11, to the unpredictability of design-related risks was significant.

Consequently, the results discussed in this section demonstrated that some complexity categories were more closely correlated with the specific risk factors. Based on the quantitative data of 11 mega construction projects, it can be deduced that complexity and risk are interrelated. However, further analysis is required to elucidate the nature of this relationship.

4.2 Qualitative Findings: Conceptual Framework

The quantitative analyses employed in the previous section reflected the situation at the beginning and end of the projects. Even though these analyses revealed that complexity could be a factor affecting the risk, conceptualizing their relationships with a cause-effect framework would be an oversimplified approach. During the interviews, managers of mega construction projects mentioned several cases that shed light on the multi-level interactions that emerge throughout the different phases of the project. Since the non-linear and dynamic relationship between complexity and risk cannot be unveiled with the findings of the quantitative analysis only, the qualitative data obtained from the interview transcripts were analyzed to build a data-driven conceptual framework. Based on the thematic analysis approach described in Section 3.1.2.2, a conceptual framework was developed to untangle the links between complexity and risk in mega construction projects. Besides the complexity and risk, the uncertainty and management strategies were involved in the framework as the other main concepts. Although this study principally focused on the relationship between complexity and risk, uncertainty has also been considered a risk source, as discussed in Section 2.1.6. Moreover, the influence of management strategies on the complexity or risk has been reported by many studies (Charkhakan

& Heravi, 2018; Maylor & Turner, 2017; Zhang, 2016; Zhu & Mostafavi, 2017). Since the narratives of the interviewees aligned with the literature, the uncertainty and management strategies appeared as the other themes affecting the relationship between complexity and risk in the conceptual framework. The components of the conceptual framework represented in Figure 4.4 are discussed further below.

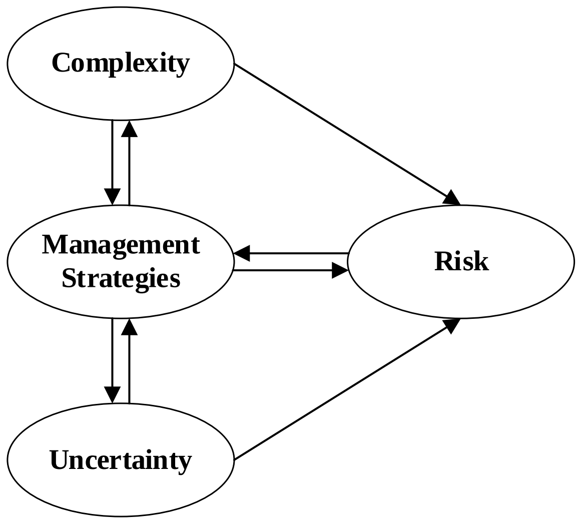


Figure 4.4. Conceptual Framework of Complexity and Risk Relationship (adapted from Erol et al., 2020)

The qualitative data of the investigated projects showed that uncertainty could be considered an important source of risk events. In one of the investigated projects, archaeological remains found during the excavation work were the most significant reason for delay that almost doubled the project duration. The imperfect information about the soil conditions exemplified the epistemic uncertainty in this project. Similarly, many participants referred to the negative impact of the currency fluctuations on their project budget, which represents the risk events inflicted by the aleatory uncertainty. Participants also mentioned management strategies they developed for the uncertainties identified at the front-end of the project. For example, a technical office manager explained that they utilized an insurance strategy to transfer the risk in case of any shipping damage in the critical procurement items of the project.

The analysis of the interview data also revealed that complexity could be another reason for the emergence of risk events in a project. The influence of complexity on risk depends on how it is treated. While some complexity factors may not be manageable, the impact of some other factors is directly related to the effectiveness of the strategies used. In one of the cases, the performance problems caused by the strategic importance of the project exemplified the former. There was a political will that compelled the contractor to open the facility earlier than the specified completion date. Since the project was commissioned before completing the construction, the project teams were able to work only three hours per day to complete the unfinished parts. As a result of limited working time, the contractor had to increase the resources at the end of the project and exceeded the budget. Thus, an unmanageable complexity factor resulted in unexpected deviations from the project targets. On the other hand, proactive management strategies may help control the risks induced by some complexity factors. The projects examined in this research contained a variety of examples regarding the risks controlled by management strategies implemented for the complexity factors. For instance, several interviewees talked about cultural management plans they utilized to mitigate the communication risks arising from cultural diversity between the project teams. In one of the pipeline projects in the data set, tracking the location of the pipes through Radio-Frequency Identification (RFID) technology to minimize the logistics risks caused by a geographically dispersed construction site constituted another example of complexity and risk relationship mediated by management strategies. In another project, the existence of several disciplines to work together was identified as the primary source of coordination risks between the project teams. The action taken to manage this complexity was using the clash detection feature of Building Information Modeling (BIM). The project coordinator indicated that the following: "We were still facing [coordination] problems between mechanical and electrical disciplines despite the existence of BIM. However, there would have been more conflicts if we had not used BIM." Sometimes, management strategies implemented for complexity factors may even lead to opportunities in the project. As discussed in

Section 2.1.5, complexity has been predominantly accepted as a negative term in the project management literature. However, the findings from the qualitative analysis of this research pointed out that complexity may decrease the risk or improve the innovation potential of projects. One of the participants stated that: "It [complexity] helped us better prepare for the project. We had to think about alternatives and take pro-active actions to deal with complexity factors. With contingency planning, increasing resources, and finding innovative solutions, we aimed to build a resilient project system. Complexity affected us in a positive way." In one of the projects, changing the construction method as a response to high technical complexity exemplified the opportunity provided by management strategies. The strategy employed was prefabricating the major structural components of the project and assembling them at the construction site. The project manager noted that: "Construction process looked very challenging in the beginning, but then it became the easiest part of the project." As a summary, on the one hand, complexity may trigger the emergence of risk events as threats. On the other hand, when combined with the appropriate management strategies, it may reduce the threats and even result in opportunities.

It should also be noted that emergent or deliberate strategies employed to cope with a specific complexity factor or uncertainty may introduce new complexity factors or uncertainties into the project system. For example, although the prefabrication strategy mentioned above helped to decrease the technical risk, it increased the complexity and uncertainty in the supply chain at the same time. For this reason, the management strategies node in Figure 4.4 is connected to complexity and uncertainty nodes with the two-way arrows. In addition to management strategies implemented for complexity and uncertainty, there are also some resilience strategies to alleviate the damage induced by risk events that happened in the project. Therefore, the management strategies node in Figure 4.4 has another two-way arrow linked with the risk node. Furthermore, though the resilience strategies are essential for the functioning of the project system, they may also give rise to new complexity factors or uncertainties. For instance, one of the participants explained that they suffered from a significant delay due to expropriation problems in the project. In order to overcome this problem, the contractor changed the route of the construction by modifying the initial design. The revisions in the project also caused the change in the construction method and, consequently, the technical complexity factors identified at the beginning of the project transformed into a new form. This example revealed that there could be a cyclic relationship between complexity and risk. Even though complexity is usually considered a source of risk, sometimes it may also be the outcome of risk events. Hence, the findings of this study affirmed the duality of complexity and risk, which has been mentioned by Thomé et al. (2016).

Consequently, the qualitative findings discussed in this section helped to explain the nature of the relationship between complexity and risk. The conceptual framework in Figure 4.4 unveiled the reciprocal and dynamic links between risk-related concepts. Each link introduced in the framework can bring different characteristics to the project system. Moreover, the existence of positive feedback loops exacerbates the level of unpredictability in mega construction projects, which may constitute a major challenge for the managers during the risk assessment.

4.3 Integrated Risk Assessment Process (IRAP)

The quantitative and qualitative parts of the mixed-methods approach utilized in this study examined the relationship between complexity and risk in mega construction projects from different perspectives. Integrating their findings can clarify the implications of this relationship for project risk management. The numerical analyses employed in the quantitative part showed that complexity might affect the predictability of the risk impact. The conceptual framework introduced with the qualitative analysis, on the other hand, shed light on how complexity and risk interact with each other. In addition to the complexity, the framework conceptualized uncertainty as another source of risk events. It also revealed the role of management strategies in the relationships among risk-related concepts. Management strategies may mediate the way that complexity and uncertainty impact the risk. Moreover, due to a management strategy developed for a specific factor, new complexity and uncertainty factors may be introduced into the project system, which in turn may lead to secondary risks. As a result, when the findings from the quantitative and qualitative parts are integrated, it can be deduced that all factors that have an impact on the risk events should be handled together during the risk assessment phase. The glossary of the Society for Risk Analysis (SRA, 2015, p. 8) defined risk assessment as a "systematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge." Accordingly, a holistic risk assessment process that can integrate the aforementioned concepts may facilitate to perceive the risks in a project. In this respect, an integrated risk assessment approach was suggested so that more realistic scenarios about mega construction projects can be developed. The process diagram of the Integrated Risk Assessment Process (IRAP) proposed in this research is shown in Figure 4.5.

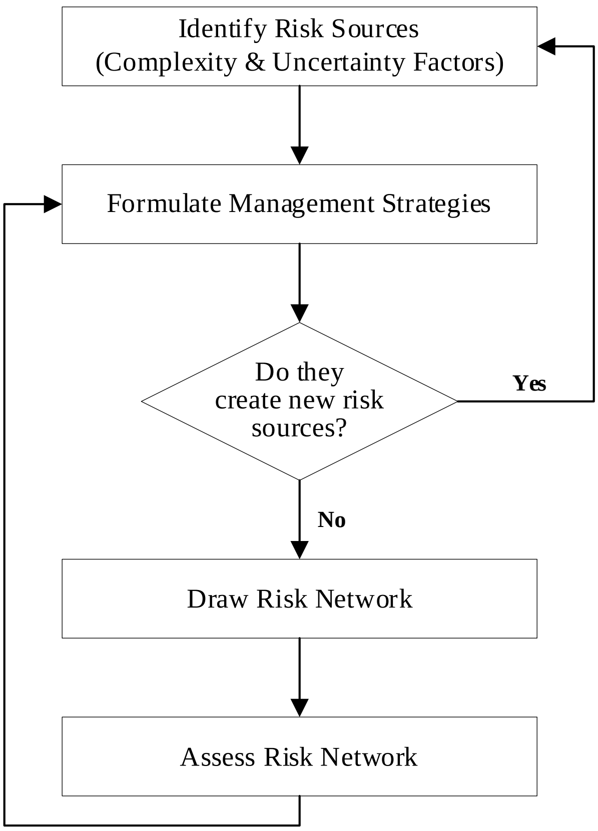


Figure 4.5. Integrated Risk Assessment Process (IRAP)

IRAP starts with identifying the risk sources (complexity and uncertainty) in the project. At the commencement stage, the complexity factors can be identified by analyzing the characteristic features of the project, such as size, number of stakeholders, and technical difficulty. These factors constitute the "static complexity" of the project. Similarly, based on the existing knowledge and experience of the project management team, some uncertainty factors can be identified at the front-end of the project. The second step of IRAP is formulating management strategies for the identified factors. The aim of these strategies is not only facilitating the management of complexity and uncertainty but also reducing their magnitude. However, as shown by the research findings, strategies formulated to deal with existing factors may trigger the emergence of new risk sources. For this reason, there is an iterative process between the first and second steps of IRAP. While the outcome of the traditional assessment methods is usually a risk checklist, the iterative process of IRAP is expected to result in a network that maps risk events to complexity and uncertainty factors, together with the strategies formulated to manage them. The last step of IRAP is analyzing the constructed risk network. The network analysis is a crucial step of the proposed risk assessment process since it enables managers to rate the risk sources by considering the interdependencies between various factors. Different analytical techniques can be applied to analyze the factors in the risk network. The analysis could help to prioritize the risk sources, update previous strategies, and develop resilience strategies to recover from the adverse impact of identified risk events as quickly as possible. As the precautions taken according to the network analysis may introduce new risk sources, there is a feedback loop to repeat the previous steps prior to the finalization of IRAP. Moreover, IRAP is based on analyzing the risks in the project with information available at a specific time. As the project progresses, a "dynamic complexity" may emerge due to the transformation of the existing factors or involvement of new ones. Similarly, uncertainties identified in the beginning may decrease, or new uncertainty factors can appear. The dynamic nature of the projects also requires updating the existing management strategies as well as formulating new plans. Therefore, IRAP should be repeated periodically throughout the project.

Consequently, IRAP illustrated in Figure 4.5 proposed a risk assessment approach for mega construction projects by integrating complexity, uncertainty, management strategies, and risk concepts. However, it should be noted that IRAP was presented as a conceptual model to explain how complexity-based thinking can be incorporated into the risk assessment process. It requires to be supported by analytical techniques in order to test its validity in real applications. In this respect, the next chapter reports the findings of the analytical model developed to operationalize the conceptual model.

CHAPTER 5

AN ANALYTICAL MODEL FOR RISK QUANTIFICATION

This chapter discusses the findings from the analytical model development studies in the second phase of the research. As described in Section 3.2.1, an Analytic Network Process (ANP) model was developed in order to make the Integrated Risk Assessment Process (IRAP) functional. The ANP model serves to establish the weights of the parameters to be rated during the risk assessment of mega construction projects by taking the interrelations between risk-related factors into account. In this respect, the following sections present the components of the ANP model, its weights calculated based on the two-round Delphi study, as well as the benefits and shortcomings of the ANP-based risk assessment model.

5.1 Components of the ANP Model

The first step in developing the ANP model was determining the components. Since the analytical model serves to operationalize the conceptual model, complexity, uncertainty, management strategies, and risk concepts in IRAP were selected as the components of the ANP model. Then, a risk assessment model was developed by establishing links between these four themes. The overview of the proposed model is shown in Figure 5.1.

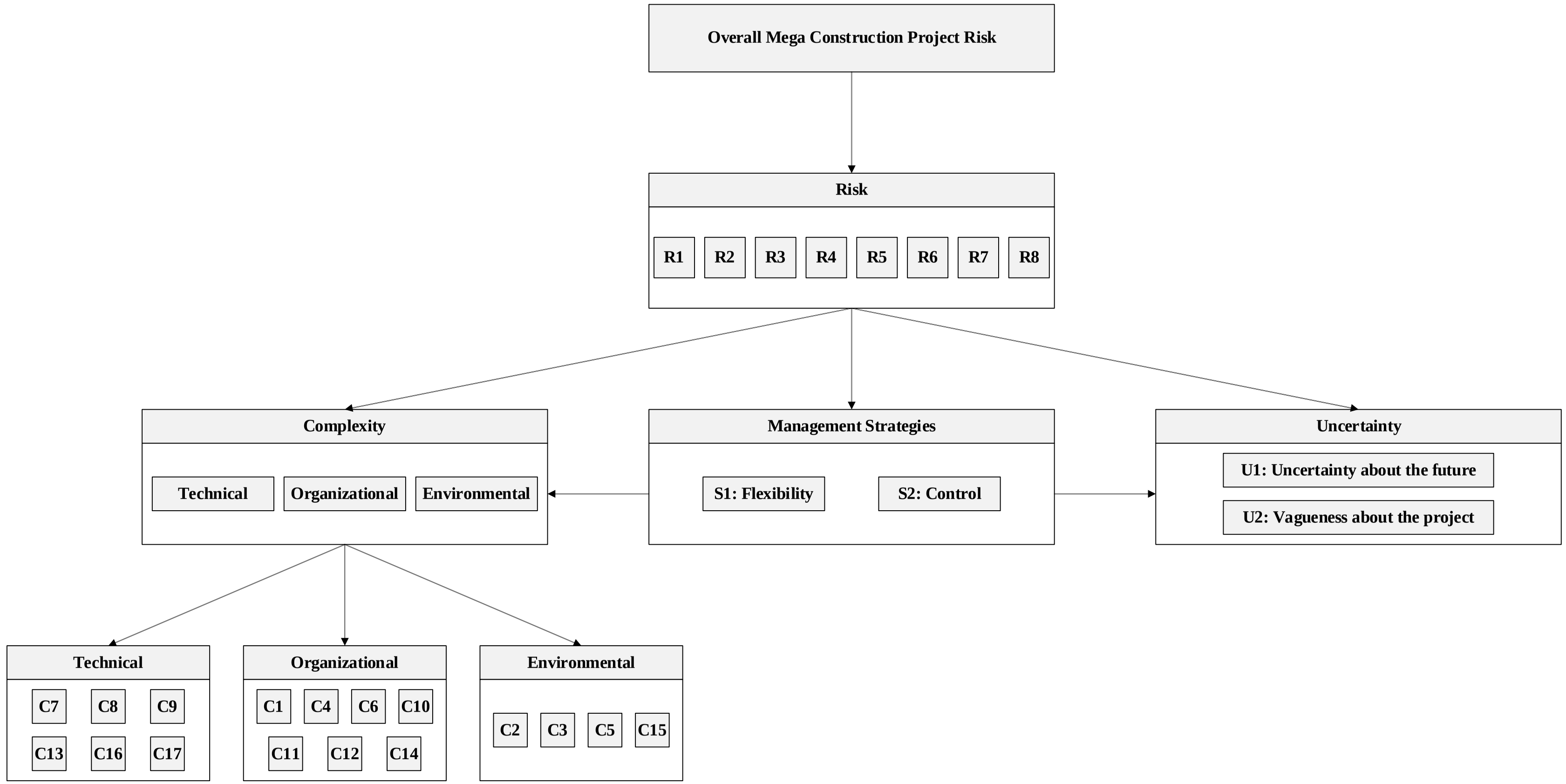


Figure 5.1. ANP Model

Although the analytical model presented in Figure 5.1 basically has a hierarchical structure, the interlinks between the management strategies and other main clusters turn it into a network structure. The node at the highest level of the hierarchy indicates that measuring the overall risk of a mega construction project is the primary goal of the model. The risk score is calculated over eight risk factors given in Table 3.2. These risk factors are connected to three main clusters. In accordance with the conceptual model, complexity, uncertainty, and the secondary risks stem from the management strategies are the main sources of the risk events. The complexity cluster is composed of 17 factors under the technical, organizational, and environmental categories, as given in Table 3.1. The uncertainty cluster contains two main categories according to the uncertainty types classified by Aven (2016). As described in Section 2.1.6, uncertainty about the future (U1) represents the stochastic variations or randomness in the future state of the parameters, while vagueness about the project (U2) refers to imperfect information or lack of knowledge related to the project parameters. Management strategies cluster, on the other hand, reflect the two distinct approaches categorized by Koppenjan et al. (2011) to address the complexity and uncertainty, as discussed in Section 2.1.5. The flexibility (S1) strategy is based on the “prepare-and-commit” approach that focuses on adapting to the changes that happen in different stages of the project. In contrast, the control (S2) strategy has the “predict-and-control” perspective with a more rigid and detailed plan to be followed throughout the project.

Consequently, the overall risk of a mega construction project can be calculated by rating the parameters at the lowest level of the hierarchy. These parameters are 17 complexity factors and two uncertainty categories. Even though management strategies are not the parameters to be rated during the risk assessment, they constitute the network structure of the model by linking the other parameters. According to this structure, initially, the effectiveness of the flexibility and control strategies on the eight risk factors are evaluated. Then, the contribution of the three complexity and two uncertainty categories to risk factors are compared separately when flexibility or control strategies are implemented. Thus, management strategies influence the weights of the complexity and uncertainty categories in the risk assessment model. Furthermore, since the implemented strategies affect the level of complexity or uncertainty, they are considered during the rating of these parameters as well.

The analytical model presents a comprehensive risk assessment approach for mega construction projects by integrating the risk-related factors. However, there were some assumptions to simplify the application of ANP. These assumptions are listed as follows:

- The relationship between complexity and risk was established by connecting the risk factors to the three complexity categories only. If they had been linked to the 17 complexity factors, the number of pairwise comparisons would have increased significantly.
- The possible relationships between the three complexity categories were not taken into account.
- Uncertainty was represented by two generic categories only. Nevertheless, it is possible to define new factors under these categories by distributing their weights to the associated factors.
- The relationship between complexity and uncertainty was set through management strategies. The possible direct interactions between them were ignored.
- Management strategies refer to all actions taken for either complexity, uncertainty, or risk. However, the direct impact of management strategies on the complexity and uncertainty was not evaluated during the pairwise comparisons since they were not linked to the complexity and uncertainty categories with two-way arrows. In other words, the effectiveness of the flexibility and control strategies were considered only for the risk factors induced by complexity and uncertainty.

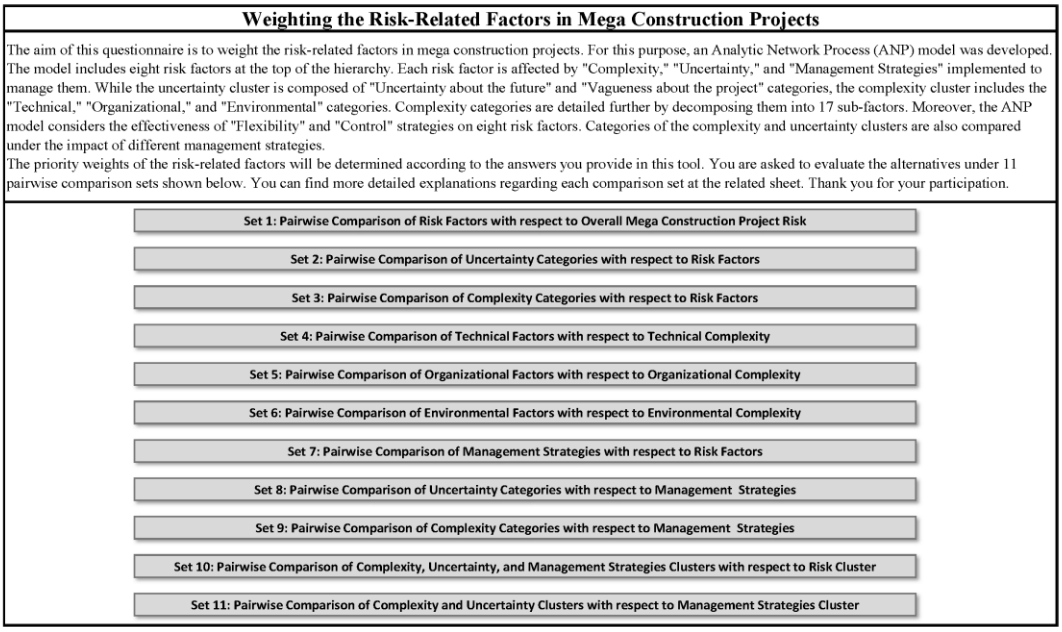
5.2 Weights of the ANP Model

Following the finalization of the ANP model, the next step was comparing the components with each other to determine the weights to be used for risk quantification. For this purpose, 122 pairwise comparisons that constituted 34 comparison matrices were identified under 11 comparison sets. Details of the comparison sets are given in Table 5.1.

Table 5.1. Comparison Sets of the ANP Model

ID	Pairwise Comparison Set	Number of Comparisons	Number of Matrices
1	Risk Factors (R1 to R8) with respect to Overall Mega Construction Project Risk	28	1
2	Uncertainty Categories (U1 & U2) with respect to Risk Factors (R1 to R8)	8	8
3	Complexity Categories (T, O, & E) with respect to Risk Factors (R1 to R8)	24	8
4	Technical Factors (C7, C8, C9, C13, C16, & C17) with respect to Technical Complexity	15	1
5	Organizational Factors (C1, C4, C6, C10, C11, C12, & C14) with respect to Organizational Complexity	21	1
6	Environmental Factors (C2, C3, C5, & C15) with respect to Environmental Complexity	6	1
7	Management Strategies (S1 & S2) with respect to Risk Factors (R1 to R8)	8	8
8	Uncertainty Categories (U1 & U2) with respect to Management Strategies (S1 & S2)	2	2
9	Complexity Categories (T, O, & E) with respect to Management Strategies (S1 & S2)	6	2
10	Complexity, Uncertainty, and Management Strategies Clusters with respect to Risk Cluster	3	1
11	Complexity and Uncertainty Clusters with respect to Management Strategies Cluster	1	1

As explained in Section 3.2.2, the comparison sets listed in Table 5.1 were evaluated by five experts with a two-round Delphi study. In the first round of the Delphi study, the experts made comparisons separately with the help of the data collection tool. Figure 5.2 demonstrates the index page of the tool, which contains the links to 11 comparison sets listed in Table 5.1.


Weighting the Risk-Related Factors in Mega Construction Projects

The aim of this questionnaire is to weight the risk-related factors in mega construction projects. For this purpose, an Analytic Network Process (ANP) model was developed. The model includes eight risk factors at the top of the hierarchy. Each risk factor is affected by "Complexity," "Uncertainty," and "Management Strategies" implemented to manage them. While the uncertainty cluster is composed of "Uncertainty about the future" and "Vagueness about the project" categories, the complexity cluster includes the "Technical," "Organizational," and "Environmental" categories. Complexity categories are detailed further by decomposing them into 17 sub-factors. Moreover, the ANP model considers the effectiveness of "Flexibility" and "Control" strategies on eight risk factors. Categories of the complexity and uncertainty clusters are also compared under the impact of different management strategies.
The priority weights of the risk-related factors will be determined according to the answers you provide in this tool. You are asked to evaluate the alternatives under 11 pairwise comparison sets shown below. You can find more detailed explanations regarding each comparison set at the related sheet. Thank you for your participation.

Set 1: Pairwise Comparison of Risk Factors with respect to Overall Mega Construction Project Risk

Set 2: Pairwise Comparison of Uncertainty Categories with respect to Risk Factors

Set 3: Pairwise Comparison of Complexity Categories with respect to Risk Factors

Set 4: Pairwise Comparison of Technical Factors with respect to Technical Complexity

Set 5: Pairwise Comparison of Organizational Factors with respect to Organizational Complexity

Set 6: Pairwise Comparison of Environmental Factors with respect to Environmental Complexity

Set 7: Pairwise Comparison of Management Strategies with respect to Risk Factors

Set 8: Pairwise Comparison of Uncertainty Categories with respect to Management Strategies

Set 9: Pairwise Comparison of Complexity Categories with respect to Management Strategies

Set 10: Pairwise Comparison of Complexity, Uncertainty, and Management Strategies Clusters with respect to Risk Cluster

Set 11: Pairwise Comparison of Complexity and Uncertainty Clusters with respect to Management Strategies Cluster

Figure 5.2. Index Page of the Data Collection Tool

Consequently, five experts followed the procedure described in Section 3.2.3.1 to complete 122 pairwise comparisons under 11 comparison sets. Thanks to the data collection tool and the competence of experts, there was no inconsistency or invalid selection in any of the comparisons. Since there are three possible options for the pairwise comparisons, four categories were identified related to the selections of the experts in the first round. In Category A, all experts prefer the same option. According to Category B, four experts select the same option, while other expert picks another option. In Category C, there is an option chosen by three experts. The remaining two experts may either select the same alternative option or favor different alternatives. Finally, Category D contains the two options chosen by two experts and the other option preferred by the fifth expert. Table 5.2 presents the number of items that belong to these categories for 122 pairwise comparisons in the first round of the Delphi study.

Table 5.2. Selections Made for the Pairwise Comparisons in the First Round

Category	Frequency	Percentage
Category A	38	31.1%
Category B	45	36.9%
Category C	33	27.1%
Category D	6	4.9%

After the successful completion of the first round, a panel was conducted in the second round of the Delphi study, which aims to build a consensus among the experts for their selections. According to Table 5.2, at least four experts selected the same option in 68% of the pairwise comparisons in the first round. For these comparisons, the consensus was reached rather quickly. Experts suggested using the average of the initial ratings for the comparisons that belong to Category A. With a few exceptions, the majority opinion was accepted for the comparisons that included two alternative options in both Category B and some part of Category C. On the other hand, there were also some comparisons that contained three alternative options in Category D and some part of Category C. The discussions for these items took more time to settle. When the experts agreed on the comparisons, their selections were immediately entered into the data collection tool to check the consistency ratio. For a few comparisons that the experts remained unsettled, different alternatives were tried in the tool to inform them about the consistency of these alternatives. Thus, experts reached a decision about these comparisons.

As a result of the two-round Delphi study, the pairwise comparisons of the experts were refined. Based on 122 pairwise comparisons, 34 consolidated comparison matrices were obtained under 11 comparison sets. For all of these matrices, the consistency ratio calculated by Equations (3.6 and 3.7) was within the allowed limit.

The consolidated comparison matrices are provided in Appendix B. These matrices were utilized to derive local priorities. Then, the local priorities were converted into global priorities with the supermatrix calculations. At the end of this process, the weights of 17 complexity factors and two uncertainty categories to be used in risk assessment of mega construction projects were obtained. In order to check the accuracy of the calculations, the pairwise comparisons obtained from the Delphi study were analyzed in the Super Decisions software by creating the same analytical model. With the "identity at sinks" algorithm of the software, the same weights were obtained for 17 complexity factors and two uncertainty categories. The following two sections present and discuss the results of local and global priorities.

5.2.1 Local Priorities

The local priorities were derived from the priorities vector calculated by Equation (3.5) for each consolidated comparison matrix provided in Appendix B. In this regard, the subsequent sections report the local priorities that belong to 11 comparison sets.

5.2.1.1 Comparison Set 1

In this set, country-related political and economic risks (R1), financial risks (R2), contractual risks (R3), owner-related risks (R4), procurement risks (R5), project management and organization risks (R6), construction-related/technological risks (R7), and design risks (R8) were compared with respect to their contribution to the overall risk (OR) of a mega construction project. The priorities calculated for the comparison matrix of the first set are listed in Table 5.3.

Table 5.3. Priorities in the First Comparison Set

Control Criterion	Factor	Priority (%)
OR	R1	28.94
	R2	19.39
	R3	12.32
	R4	15.30
	R5	6.00
	R6	9.11
	R7	4.08
	R8	4.86

According to Table 5.3, R1 was the most significant risk factor, followed by R2. These results demonstrate that experts place more emphasis on the external risk factors, which are usually beyond the control of project management. In contrast to uncontrollable factors, the technical risks, such as R7 and R8, were determined to be less important in terms of their contribution to the overall mega construction project risk.

5.2.1.2 Comparison Set 2

In this set, uncertainty about the future (U1) and vagueness about the project (U2) categories were compared with respect to their contribution to each risk factor. The priorities calculated for the eight comparison matrices of the second set are listed in Table 5.4.

Table 5.4. Priorities in the Second Comparison Set

Control Criterion	Factor	Priority (%)
R1	U1	87.50
	U2	12.50
R2	U1	85.71
	U2	14.29
R3	U1	20.00
	U2	80.00
R4	U1	33.33
	U2	66.67
R5	U1	50.00
	U2	50.00
R6	U1	25.00
	U2	75.00
R7	U1	20.00
	U2	80.00
R8	U1	16.67
	U2	83.33

According to Table 5.4, U1 was a more influential uncertainty type for R1 and R2. In other words, uncertainty caused by the stochastic variations was considered a more important source for the external risk factors. On the other hand, U2 was more significant than U1 for most of the risks. In particular, R8, R3, and R7 were more closely associated with the uncertainty caused by the lack of knowledge about the project system. The experts evaluated the impact of U1 and U2 on R5 as equal.

5.2.1.3 Comparison Set 3

In this set, technical (T), organizational (O), and environmental (E) complexity categories were compared with respect to their contribution to each risk factor. The priorities calculated for the eight comparison matrices of the third set are listed in Table 5.5.

Table 5.5. Priorities in the Third Comparison Set

Control Criterion	Factor	Priority (%)
R1	T	6.03
	O	23.12
	E	70.85
R2	T	16.92
	O	38.74
	E	44.34
R3	T	13.97
	O	52.78
	E	33.25
R4	T	23.18
	O	58.42
	E	18.40
R5	T	25.99
	O	41.26
	E	32.75
R6	T	22.55
	O	67.38
	E	10.07
R7	T	74.29
	O	19.39
	E	6.32
R8	T	75.83
	O	15.12
	E	9.05

According to Table 5.5, environmental complexity was more significant for the external risk factors (R1 and R2), whereas technical complexity was more impactful for the technical risk factors (R7 and R8). Furthermore, organizational complexity had the highest contribution percentage for R6. These results coincided with the quantitative findings obtained in the first phase of the research to a large extent.

However, for R3, R4, and R5, organizational complexity was selected as the most significant category during the pairwise comparisons though the technical complexity was more important according to the earlier findings. The difference may stem from the fact that while the previous findings estimated the relationship between complexity and risk with an indirect analysis of 11 projects, the pairwise comparisons were directly based on the general opinion of the experts. Regardless of their differences, both results propound the correlation between the specific complexity and risk factors.

5.2.1.4 Comparison Set 4

In this set, lack of technical experience (C7), changes in the project scope (C8), unrealistic project targets (C9), multiple critical paths (parallel activities) (C13), technological novelty of the project (C16), and originality of the project design (C17) were compared with respect to their contribution to technical (T) complexity. The priorities calculated for the comparison matrix of the fourth set are listed in Table 5.6.

Table 5.6. Priorities in the Fourth Comparison Set

Control Criterion	Factor	Priority (%)
T	C7	25.62
	C8	36.11
	C9	14.36
	C13	11.65
	C16	5.98
	C17	6.28

According to Table 5.6, C8 was the top factor that increases the technical complexity of mega construction projects. On the other hand, factors more closely related to the construction operations, such as C16 and C17, were considered less significant.

However, as C7 had the second-highest percentage, the results also indicate that technical complexity is amplified when the technical experience is insufficient.

5.2.1.5 Comparison Set 5

In this set, size of the project (C1), variety of financial institutions or sponsors (C4), inadequacy of the contract (C6), unavailability of resources (labor, material, equipment) (C10), interactions between the project disciplines (C11), cultural diversity (C12), and staff and equipment mobility (C14) were compared with respect to their contribution to organizational (O) complexity. The priorities calculated for the comparison matrix of the fifth set are listed in Table 5.7.

Table 5.7. Priorities in the Fifth Comparison Set

Control Criterion	Factor	Priority (%)
O	C1	31.69
	C4	18.60
	C6	12.06
	C10	8.73
	C11	22.71
	C12	2.42
	C14	3.79

According to Table 5.7, C1 had the highest percentage, which implies that the magnitude of a mega construction project is the biggest contributor to organizational complexity. C11 was another important organizational complexity indicator. The impact of the C12 and C14, on the other hand, was evaluated as very low.

5.2.1.6 Comparison Set 6

In this set, strategic importance of the project (C2), political or macroeconomic instability (C3), interactions between the stakeholders (C5), and physical and logistic constraints (C15) were compared with respect to their contribution to environmental (E) complexity. The priorities calculated for the comparison matrix of the sixth set are listed in Table 5.8.

Table 5.8. Priorities in the Sixth Comparison Set

Control Criterion	Factor	Priority (%)
E	C2	15.12
	C3	45.93
	C5	34.84
	C15	4.11

According to Table 5.8, C3 was the most significant environmental complexity factor. This result reveals that political and economic factors contribute more to the environmental complexity of mega construction projects. C5, which is related to the internal dynamics of the projects, was the second most important environmental complexity indicator. While the impact of C2 was limited, C15 was the least significant factor.

5.2.1.7 Comparison Set 7

In this set, flexibility (S1) and control (S2) strategies were compared with respect to their impact on each risk factor. The priorities calculated for the eight comparison matrices of the seventh set are listed in Table 5.9.

Table 5.9. Priorities in the Seventh Comparison Set

Control Criterion	Factor	Priority (%)
R1	S1	88.89
	S2	11.11
R2	S1	80.00
	S2	20.00
R3	S1	33.33
	S2	66.67
R4	S1	50.00
	S2	50.00
R5	S1	66.67
	S2	33.33
R6	S1	16.67
	S2	83.33
R7	S1	25.00
	S2	75.00
R8	S1	33.33
	S2	66.67

According to Table 5.9, S1 was a more effective strategy, particularly for R1 and R2. It means that developing flexible approaches for adapting to the changes was considered more appropriate for uncontrollable risk factors. Since the external conditions affect the procurement, too, the priority of S1 was higher for R5. On the other hand, S2 was more effective than S1 for R3, R6, R7, and R8. In particular, experts thought that a robust planning approach could be more useful for the managerial and organizational issues of the project. On the other hand, the effectiveness of S1 and S2 was considered equal for R4. When all findings are interpreted together, it can be deduced that these two strategies should be used in balance to manage different risk factors.

5.2.1.8 Comparison Set 8

In this set, uncertainty about the future (U1) and vagueness about the project (U2) categories were compared with respect to their contribution to risk factors when flexibility (S1) or control (S2) strategies are implemented. The priorities calculated for the two comparison matrices of the eighth set are listed in Table 5.10.

Table 5.10. Priorities in the Eighth Comparison Set

Control Criterion	Factor	Priority (%)
S1	U1	33.33
	U2	66.67
S2	U1	83.33
	U2	16.67

According to Table 5.10, U2 was a more important risk source than U1 when S1 is the strategy used. In contrast to this result, U1 was a more significant uncertainty type under the effect of S2. These results manifest that while the “predict-and-control” approach is more effective for the “epistemic uncertainty,” the “prepare-and-commit” approach is better suited for the “aleatory uncertainty.”

5.2.1.9 Comparison Set 9

In this set, technical (T), organizational (O), and environmental (E) complexity categories were compared with respect to their contribution to risk factors when flexibility (S1) or control (S2) strategies are implemented. The priorities calculated for the two comparison matrices of the ninth set are listed in Table 5.11.

Table 5.11. Priorities in the Ninth Comparison Set

Control Criterion	Factor	Priority (%)
S1	T	16.34
	O	29.70
	E	53.96
S2	T	10.61
	O	19.29
	E	70.10

According to Table 5.11, environmental complexity was the most significant risk source, regardless of the implemented strategy. However, there was a considerable reduction in its influence when S1 is the strategy used. Therefore, flexible management strategies could be more effective in dealing with environmental complexity.

5.2.1.10 Comparison Set 10

In this set, comparisons are made for the clusters. Accordingly, complexity (C), uncertainty (U), and management strategies (MS) clusters were compared with respect to their contribution to the risk (R). The priorities calculated for the comparison matrix of the tenth set are listed in Table 5.12.

Table 5.12. Priorities in the Tenth Comparison Set

Control Criterion	Cluster	Priority (%)
R	C	43.30
	U	46.65
	MS	10.05

According to Table 5.12, experts assigned almost equal importance to complexity and uncertainty in terms of their contribution to risk factors, strengthening the central argument of this research that complexity should be integrated into the risk assessment process. Moreover, the results signify that one out of 10 risk events is a secondary risk that stems from management strategies implemented for other factors.

5.2.1.11 Comparison Set 11

In this set, comparisons are made for the clusters. Accordingly, complexity (C) and uncertainty (U) clusters were compared with respect to their contribution to risks caused by management strategies (MS). The priorities calculated for the comparison matrix of the eleventh set are listed in Table 5.13.

Table 5.13. Priorities in the Eleventh Comparison Set

Control Criterion	Cluster	Priority (%)
MS	C	50.00
	U	50.00

According to Table 5.13, the secondary risks caused by management strategies implemented to deal with either complexity or uncertainty have the same frequency. This result means that the weight calculated for management strategies in the previous comparison set will be distributed to the complexity and uncertainty clusters equally.

5.2.2 Global Priorities

The global priorities of the ANP model were obtained according to the supermatrix calculations explained in Section 3.2.3.4. The first step of these calculations was gathering the local priorities presented in the previous section within an unweighted supermatrix. Based on this operation, a 33 by 33 unweighted supermatrix was constructed. The rows and columns of this matrix were composed of 17 complexity factors (C1 to C17), three complexity categories (T, O, and E), two uncertainty categories (U1 and U2), two management strategies (S1 and S2), eight risk factors (R1 to R8), and the overall risk of the mega construction project (OR). The unweighted supermatrix of this study is tabulated in Appendix C. In the second step, the cluster weights obtained from the last two comparison sets served to convert the unweighted supermatrix into a weighted supermatrix. Accordingly, priority weights given in Table 5.12 and Table 5.13 were multiplied with the corresponding numbers in the unweighted supermatrix. Based on Table 5.12, values regarding the complexity, uncertainty, and management strategies clusters in the columns belong to risk factors were multiplied by 0.4330, 0.4665, and 0.1005, respectively. Similarly, values regarding the complexity and uncertainty clusters in the columns belong to management strategies were multiplied by 0.50, according to Table 5.13. Thus, a column stochastic matrix was obtained, where the summation of the values in each of 33 columns became one. The weighted supermatrix is provided in Appendix D. Finally, the weighted supermatrix was raised to powers until it converges. In this study, the column values were stabilized after the fourth power of the weighted supermatrix. The resulting limit supermatrix is presented in Appendix E.

Consequently, the relative importance weight of each component in the model was given by the global priorities in the limit supermatrix. The weights derived for 17 complexity factors and two uncertainty categories to assess eight risk factors are shown in Table 5.14.

Table 5.14. Importance Weights of the Risk Sources for Each Risk Factor

ID	R1	R2	R3	R4	R5	R6	R7	R8
C1	0.03626	0.05755	0.07605	0.08405	0.06079	0.09580	0.03009	0.02438
C2	0.05062	0.03337	0.02668	0.01676	0.02594	0.01171	0.00916	0.01084
C3	0.15379	0.10139	0.08107	0.05091	0.07883	0.03558	0.02783	0.03294
C4	0.02129	0.03379	0.04465	0.04935	0.03569	0.05625	0.01767	0.01431
C5	0.11666	0.07692	0.06150	0.03862	0.05980	0.02699	0.02111	0.02499
C6	0.01380	0.02190	0.02894	0.03198	0.02313	0.03645	0.01145	0.00928
C7	0.00872	0.02073	0.01711	0.02746	0.03070	0.02651	0.08398	0.08574
C8	0.01228	0.02922	0.02411	0.03870	0.04327	0.03737	0.11835	0.12085
C9	0.00488	0.01162	0.00959	0.01539	0.01720	0.01486	0.04706	0.04805
C10	0.00999	0.01586	0.02095	0.02316	0.01675	0.02640	0.00829	0.00672
C11	0.02599	0.04124	0.05450	0.06024	0.04356	0.06865	0.02156	0.01747
C12	0.00278	0.00441	0.00582	0.00643	0.00465	0.00733	0.00230	0.00187
C13	0.00396	0.00943	0.00778	0.01248	0.01396	0.01206	0.03818	0.03899
C14	0.00434	0.00688	0.00910	0.01006	0.00727	0.01146	0.00360	0.00292
C15	0.01376	0.00907	0.00726	0.00456	0.00705	0.00318	0.00249	0.00295
C16	0.00203	0.00484	0.00399	0.00641	0.00716	0.00619	0.01960	0.02001
C17	0.00213	0.00508	0.00419	0.00673	0.00752	0.00649	0.02057	0.02100
U1	0.42770	0.42161	0.12679	0.18480	0.25836	0.15430	0.12889	0.11124
U2	0.08902	0.09511	0.38992	0.33192	0.25836	0.36241	0.38783	0.40547

The limit supermatrix also contains the weights for the overall risk of a mega construction project in the last column. These values were obtained by taking the weighted average of the numbers in Table 5.14 using the priorities given in Table 5.3 for eight risk factors. The resulting weights of 17 complexity factors and two uncertainty categories to assess the overall mega construction project risk are compiled in Table 5.15.

Table 5.15. Importance Weights of the Risk Sources for Overall Project Risk

ID	Overall Mega Construction Project Risk
C1	0.05867
C2	0.03049
C3	0.09264
C4	0.03445
C5	0.07028
C6	0.02232
C7	0.02471
C8	0.03482
C9	0.01384
C10	0.01617
C11	0.04204
C12	0.00449
C13	0.01123
C14	0.00702
C15	0.00829
C16	0.00577
C17	0.00605
U1	0.28962
U2	0.22710

According to Table 5.15, political or macroeconomic instability (C3), interactions between the stakeholders (C5), and size of the project (C1) were determined the most influential complexity factors for the overall risk of a mega construction project. Among the uncertainty categories, the overall impact of the uncertainty about the future (U1) was higher. Even though the total weights of the complexity and uncertainty clusters were close to each other, as compared to the 17 complexity factors, U1 and U2 had higher weights since they represent a broader category. By summing up the values of the technical, organizational, and environmental factors, the weights of the complexity categories were calculated as 0.09642, 0.18516, and 0.20170, respectively. These numbers revealed that environmental complexity is the most significant complexity category for the overall risk, whereas the contribution of technical complexity is limited.

5.3 Benefits and Shortcomings of the ANP-based Risk Assessment Model

As a result, the weights given by the ANP model will be multiplied with the ratings assigned for complexity and uncertainty parameters during the risk assessment of a mega construction project. The main benefit of the ANP-based risk assessment model is that it can quantify the combined impact of the complexity, uncertainty, and management strategies on the risk factors. While the traditional risk quantification approaches are usually based on analyzing uncertain events, the ANP-based model allows incorporating complexity into risk assessment by considering the mediating role of management strategies as well. Even though management strategies do not include parameters to be rated during the risk assessment, the weights of the model were determined by taking the interrelations between management strategies and other parameters into account. Moreover, the impact of a management strategy will be reflected while rating the complexity or uncertainty parameter concerning this strategy. On the other hand, there are also some shortcomings of the ANP-based risk assessment model. In addition to the assumptions explained in Section 5.1 to simplify the application of ANP, the weights of the model reflect the subjective judgment of the five experts. For this reason, the model should be tested with real project data to validate its risk quantification performance. Moreover, its usage with IRAP should be exemplified and tested in a real project setting to validate the applicability of the proposed risk assessment approach. In this respect, the next chapter presents the findings of the testing and validation studies.

CHAPTER 6

TESTING AND VALIDATION STUDIES

This chapter reports the findings from the testing and validation studies in the third phase of the research. In this respect, the following section presents the risk assessment procedure of the projects in the data set, which was carried out to test the performance of the Analytic Network Process (ANP) model. Then, the details of the demonstrative case study, which was conducted to test the applicability of the ANP model and Integrated Risk Assessment Process (IRAP), are explained in the next section.

6.1 Risk Assessment of the Projects in the Data Set with the ANP Model

The risk quantification performance of the ANP model was tested using the data of 11 mega construction projects according to the procedure explained in Section 3.3.1. In this respect, the real data provided by the project managers for 17 complexity factors and two uncertainty categories were multiplied with the corresponding weights of the ANP model to calculate the scores of eight risk factors as well as the overall risk. The risk scores estimated by the ANP model were compared with the post-project risk assessment scores given by the managers to test the risk quantification performance of the model. The complexity and uncertainty data used in the risk assessment of 11 megaprojects are presented in Table 6.1.

Table 6.1. Complexity and Uncertainty Data of 11 Mega Construction Projects

ID	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
C1	3.20	3.60	3.20	2.40	2.40	3.00	0.60	5.00	4.50	5.00	2.40
C2	3.00	0.20	1.00	3.00	4.00	5.00	3.20	5.00	4.50	3.60	2.00
C3	3.20	1.60	0.20	4.00	0.40	0.40	4.00	5.00	0.40	2.00	3.50
C4	1.80	0.20	0.80	1.20	0.40	0.20	3.20	5.00	0.40	3.20	2.40
C5	4.00	2.40	1.60	4.00	3.00	5.00	4.00	1.35	2.40	4.00	2.80
C6	0.40	3.20	0.60	0.60	1.00	4.00	0.80	5.00	0.20	0.60	0.40
C7	0.88	1.80	2.25	1.65	0.65	2.63	0.63	4.28	1.24	1.80	1.29
C8	2.00	3.60	0.80	4.50	0.40	5.00	4.00	4.00	1.60	0.20	2.10
C9	0.40	1.20	0.40	2.10	0.40	2.40	2.40	2.40	0.75	0.40	2.40
C10	3.20	0.80	0.80	2.00	1.80	0.60	3.20	1.60	1.20	3.00	2.80
C11	4.00	3.20	5.00	4.00	1.20	5.00	3.20	3.20	1.80	4.00	3.00
C12	3.00	0.40	0.20	0.40	2.40	0.20	1.60	5.00	1.80	1.00	2.40
C13	5.00	3.20	0.80	1.80	1.80	3.00	1.60	5.00	3.60	4.00	2.80
C14	3.20	0.80	0.40	0.40	4.50	1.20	2.40	4.00	3.60	3.60	2.10
C15	3.00	1.20	0.40	3.20	2.80	2.40	2.80	5.00	5.00	1.50	2.80
C16	1.80	0.80	0.80	3.20	1.80	3.00	0.40	3.00	3.60	1.80	1.20
C17	0.45	0.40	4.00	4.00	1.20	4.00	2.40	1.20	3.60	1.50	2.40
U1	4.00	3.00	4.00	5.00	2.00	2.00	2.00	5.00	3.00	4.00	4.00
U2	3.00	4.00	4.00	5.00	3.00	3.00	4.00	4.00	4.00	3.00	4.00

Based on the data presented in Table 6.1, the performance of the model was tested in terms of both individual risk factors and the overall project risk. The subsequent sections report the findings from these tests.

6.1.1 Performance of the Model in terms of Individual Risk Factors

The first test regarding the risk quantification performance of the ANP model was calculating the Risk Score Prediction Error (RSPE) of each risk factor according to Equation (3.8). The parameters in the equation are tabulated in Table 6.2.

Table 6.2. Accuracy of the Model in Predicting the Scores of Risk Factors

ID	RA	RE	RSPE (%)
R1	3.68	3.09	16.13
R2	2.82	3.06	-8.46
R3	3.32	3.14	5.44
R4	3.73	3.10	16.91
R5	2.91	3.08	-5.84
R6	2.50	3.10	-24.11
R7	2.50	3.01	-20.56
R8	3.09	3.02	2.38

In Table 6.2, the RA column shows the average of the post-project risk assessment scores in 11 projects, as given in Table 4.3. The RE column, on the other hand, lists the average risk scores estimated by the ANP model. The values in this column were calculated by multiplying the complexity and uncertainty ratings given in Table 6.1 with the corresponding importance weights given in Table 5.14 and taking the averages of 11 projects. Based on RA and RE values, the RSPE of each risk factor was determined in the last column of Table 6.2.

According to these results, the prediction error of the ANP model was less than 10% for financial risks (R2), contractual risks (R3), procurement risks (R5), and design risks (R8). The model showed superior performance, especially in predicting the scores of design risks. Nonetheless, the accuracy of the model in predicting the scores of country-related political and economic risks (R1), owner-related risks (R4), project management and organization risks (R6), and construction-related/technological risks (R7) was not as good as other factors. In particular, the prediction error was greater than 20% for project management and organization risks and construction-related/technological risks. The poor performance of the model in quantifying some risk factors may be caused by the fact that participants of this study represented the perspective of the contractors only. For example, the reason why the average score of the owner-related risks estimated by the model was considerably less than the average score supplied by the participants could be explained by the bias of the project managers. In contrast to this factor, the score given by the model for the project management and organization risks was remarkably higher than the score assigned by the participants. The project managers might have underestimated the post-project score of this factor as it is more closely associated with their performance. As the average risk score of eight factors may balance the impact of the over- or under-scored risk factors, an additional performance test was carried out based on the overall risk score of each project.

6.1.2 Performance of the Model in terms of Overall Project Risk

The second test related to the risk quantification performance of the ANP model was determining the Mean Absolute Percentage Error (MAPE) of the overall project risk scores according to Equation (3.9). For this purpose, the Absolute Percentage Error (APE) of each project was calculated, as shown in Table 6.3.

Table 6.3. Accuracy of the Model in Predicting the Overall Risk Scores of Projects

ID	ORA	ORE	APE (%)
P1	3.21	3.40	5.38
P2	2.78	3.12	10.66
P3	2.81	3.41	17.51
P4	4.04	3.83	5.44
P5	2.03	2.32	12.79
P6	2.67	2.44	9.58
P7	2.86	2.69	6.23
P8	4.26	4.87	12.61
P9	2.75	2.69	2.23
P10	3.21	3.18	1.07
P11	3.29	3.75	12.24

In Table 6.3, the ORA column demonstrates the overall risk scores obtained by taking the weighted average of the post-project risk ratings for eight factors. In order to make a consistent comparison, the weighted average of the post-project scores, which are shown in Figure 4.2, was calculated using the priorities of the eight risk factors given by the ANP model in Table 5.3. On the other hand, the ORE column presents the overall risk scores estimated by the model based on multiplying the complexity and uncertainty ratings provided for each project in Table 6.1 with the importance weights given in Table 5.15. Based on ORA and ORE values, the APE of each project was determined in the last column of Table 6.3. According to these results, most of the projects had an error rate of less than 10%. The MAPE given by Equation (3.9) for all projects was 8.70%. When the highest (17.51%) and the lowest (1.07%) error rates were excluded, the MAPE was slightly reduced to 8.57%.

6.1.3 Summary of the Findings from the Risk Assessment Procedure

Consequently, the performance tests explained above revealed the potential of the ANP model in quantifying the risks of mega construction projects. Although the performance of the model in terms of quantifying R1, R4, R6, and R7 was not as good as R2, R3, R5, and R8, the prediction accuracy was considered satisfactory for the overall mega construction project risk. Except for P3, the error rate was within reasonable limits for all projects. However, besides the bias issue explained in Section 6.1.1, there were some limitations that affected the reliability of the performance tests. First of all, complexity, uncertainty, and risk are not parameters that can be measured objectively. Even though the input and output parameters of the model were supplied by the same participants, they were based on the subjective judgment of the project managers. Second, the data for each project were provided by one or two participants only. Assessing the risks with the participation of different teams may better reflect the risk levels in the projects. Finally, participants rated the parameters by considering the general situation in their projects. The complexity and uncertainty parameters assessed at a specific time of the project may represent the risks anticipated for that time frame more realistically. Thus, more tests are needed to evaluate the performance of the ANP model. In this respect, the next section presents the application of the model, together with IRAP, to a demonstrative case study.

6.2 Application of the ANP Model and IRAP to a Demonstrative Case

Risk assessment constitutes a critical phase of project risk management. It serves as a decision criterion to set the performance targets more realistically or allocate the resources more effectively in projects. For instance, the contingency budget of a project can be determined based on its risk score. Risk assessment may also be used for comparative purposes to evaluate the relative risk levels of different projects. Therefore, comprehending all factors that may affect the overall project risk is an essential task for project managers. IRAP proposed in this research could assist practitioners in identifying and quantifying the risks in their projects.

In order to test its effectiveness, IRAP was applied to a mega pipeline project according to the procedure described in Section 3.3.2. A real application could explain how to use IRAP in practice, as well as its function in project risk management. Although IRAP can be operationalized with different analytical techniques based on network analysis, the risk assessment of the case project was performed with the ANP model developed in this research. The subsequent sections introduce the demonstrative case study, describe the steps of the ANP-based quantitative risk assessment procedure, and summarize the findings from the demonstrative case study.

6.2.1 Background Information about the Project

The megaproject selected for the demonstrative case study was a transnational natural gas pipeline project. The project has significant strategic importance for the countries involved in terms of improving their competitiveness in global energy markets. In particular, it has the potential to make Turkey an alternative energy hub in the region. The project was divided into several lots in Turkey. The construction works of each lot were awarded to different contractors as sub-projects. In this research, IRAP has been applied to one of these projects with a retrospective analysis of risk-related factors. The information used in the case analysis was provided by the planning and contracts manager of the project.

The investigated project had a total length of more than 400 kilometers, where the pipeline was passing through eight provinces on its route. It was a design-bid-build project with a lump-sum contract. While the contract price was more than $400 million, the total project duration was approximately three years. The contractor of the project was a joint-venture of two Turkish and one international construction companies. The project has been completed recently without any significant cost overrun or delay. Since the project has all the characteristic features of a mega construction project, it was an appropriate case example for demonstrating the assessment of risk-related factors through IRAP.

6.2.2 Risk Assessment Procedure

Risk is a dynamic phenomenon that depends on the changing conditions of the source parameters and strategies used to manage them. For this reason, IRAP was applied to different stages of the investigated case to observe the variations in the risk level throughout the project over the quantitative risk ratings. The selected stages were the beginning, middle, and end of the project, which approximately corresponds to progress rates of 10%, 50%, and 90%.

The risk assessment procedure started with identifying risk sources in the project and the strategies developed to manage them. Then, these risk sources were rated for three stages of the project by considering the impact of the implemented strategies. The risk sources were also rated for the planning stage of the project at which management strategies are not available. Finally, based on the ANP calculations, risk assessment scores were obtained. The following sections present the details of these studies.

6.2.2.1 Identification of the Risk Sources and Management Strategies

Since the weights of the ANP model cover 17 complexity factors and two uncertainty categories, the risk sources in the case project were identified over these parameters. However, under each uncertainty category, three uncertainty factors were defined to analyze the risk sources of the project in more detail. Corresponding category weights of the ANP model were distributed to these factors equally. Thus, 17 complexity factors under the technical, organizational, and environmental categories, as well as six uncertainty factors belong to the categories of the uncertainty about the future and vagueness about the project, were analyzed for the risk assessment of the project.

The following parts scrutinize these factors to draw a comprehensive picture of the risk sources in the project. Moreover, the strategies implemented for each risk source at three different stages of the project were tabulated. For some factors, the management strategy identified in the beginning has been kept throughout the project. In contrast to them, some factors required different management actions in the later stages. Since a strategy implemented to manage a specific risk source may have a positive or negative impact on other sources, affected factors were also listed. While some management strategies directly changed the level of complexity or uncertainty in the project, others influenced the manageability of the risk sources. The information provided below for each complexity and uncertainty factor formed a basis for rating the parameters in the next section.

- **C1-Size of the Project:** The demonstrative case was a very large-scale mega construction project in terms of the budget and construction area. The size of the project has affected the management, organization, and coordination of several factors. Therefore, project management had to cope with various problems related to the size over the course of the project. Table 6.4 lists the management strategies for C1.

Table 6.4. Management Strategies Implemented for C1

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to keep the problems that can be caused by the size under control, the project was divided into two main sections. For each section, there was a spread manager and project teams responsible for their territories only. Moreover, a construction manager was charged to coordinate the technical issues between the two sections. At the top of the hierarchy, a project director was assigned to deal with other managerial problems besides the technical issues.	Dividing the project into different sections has increased the complexity in C13 and C14. However, the management structure established in the project facilitated the management of both these factors and the other complexity factors related to the organization and coordination (C5, C11, C15).
Middle (≈ 50%)	As the project progresses, the coordination problems continued to grow, especially between the areas that separated due to physical obstacles in the second section. For this reason, the second section was also divided into two parts, and a new spread manager was appointed into the third section.	Due to the new section, the complexity in C13 and C14 increased further. However, establishing a management structure similar to the other sections helped the management of both these factors and other factors mentioned in the previous stage (C5, C11, C15).
End (≈ 90%)	By keeping the existing project management structure, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C2-Strategic Importance of the Project:** As explained in Section 6.2.1, the project has strategic importance due to international agreements. There was a commitment made by Turkey to deliver the gas at a specific date. However, except for the time pressure, the strategic importance did not have a significant impact on the project complexity. In the later stages, the pressure has decreased since the project that constitutes the next phase of the construction in the other country experienced a delay. Table 6.5 lists the management strategies for C2.

Table 6.5. Management Strategies Implemented for C2

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	Although it was not possible to reduce the pressure arising from the strategic importance of the project, the complexity factor could be turned into an advantage. For example, due to the strategic importance of the project for Turkey, the contractor has some legal rights, such as tax and customs incentives. In this regard, project management focused on exploring such opportunities.	N/A
Middle (≈ 50%)	By using the existing approach, the same strategy continued to be implemented.	N/A
End (≈ 90%)	By using the existing approach, the same strategy continued to be implemented.	N/A

- **C3-Political or Macroeconomic Instability:** Due to the coup attempt occurred in Turkey at the beginning of the project, there was an unstable environment. Correspondingly, there were increases in exchange rates, which continued throughout the project. However, the project was not affected by the currency fluctuations negatively as the contract was dollar-based. On the contrary, increases in the dollar exchange rate even improved profitability since some payments of the contractor were based on Turkish Lira. On the other hand, due to the volatile environment caused by the coup attempt, the foreign company responsible for design verification did not want to come to Turkey during this time. For this reason, some design-related delays were experienced at the beginning of the project. However, the insecure environment returned to normal in the later stages of the project. Table 6.6 lists the management strategies for C3.

Table 6.6. Management Strategies Implemented for C3

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to reduce the delay caused by the coup attempt, additional measures were taken using the contingency budget of the project. Accordingly, alternative design teams were hired for design verification.	Including new teams in the project has increased the complexity in C5.
Middle (≈ 50%)	Since the delay in design verification has been resolved, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	Since the delay in design verification has been resolved, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C4-Variety of Financial Institutions or Sponsors:** The owner had financed the project by taking a loan. For this reason, the contractor did not experience any financial problems. During the project, payments were made regularly. Table 6.7 lists the management strategies for C4.

Table 6.7. Management Strategies Implemented for C4

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	Even though the contractor did not have much interaction with the lenders, a reporting system has been established to inform them about the progress of the project.	The reporting system facilitated the management of C5.
Middle (≈ 50%)	By keeping the existing reporting system, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	By keeping the existing reporting system, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C5-Interactions between the Stakeholders:** The main stakeholders of the project were the partner companies that constitute the owner and the contractor sides. As explained in Section 6.2.1, there was a joint-venture of three construction companies on the contractor side. Similarly, the owner side consisted of three investor companies. For this reason, there were too many interactions between the owner and the contractor. Especially the issues that emerged in the later stages of the project further increased the interactions. In addition to the main stakeholders, there was another company responsible for engineering and consultancy services in the project. However, shortly after the construction started, the owner terminated the contract of this company and took the responsibility of engineering and consultancy on itself. Other stakeholders of the project included lenders, suppliers, design verification teams, and the local people affected by the project. Table 6.8 lists the management strategies for C5.

Table 6.8. Management Strategies Implemented for C5

Project Stage	**Strategy**	**Other Factors Affected by the Strategy**
Beginning (≈ 10%)	In order to accelerate the decision-making and facilitate communication with the owner, a board of management that represents all contractors in the joint-venture has been established. Under the board of management, an executive board has been appointed. Although the directors on the board of management have all the decision-making authority in the project, they delegated most of this authority to the executive board. Similarly, the directors in the executive board determined the distribution of powers, such as spending limits and commitments given to the owner, between the project director, the construction manager, and spread managers. Thus, a mechanism has been established to make project-related decisions in coordination. Depending on the criticality of the issue, decisions were being taken by the project management daily, by the executive board weekly, or by the board of management monthly. Through this mechanism, it was aimed to ensure more effective communication with the owner.	Since all managerial decisions related to the complexity and uncertainty factors of this project are taken by this mechanism, all factors have been affected by the strategy.
Middle (≈ 50%)	By keeping the existing decision-making mechanism, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	By keeping the existing decision-making mechanism, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C6-Inadequacy of the Contract:** Thanks to the experience gained in the previous lots, the owner had drafted a detailed and well-defined contract. However, from the viewpoint of the contractor, it was an inflexible contract that allocates most of the risks on itself and restricts the claim rights except in extraordinary circumstances. Despite its limitations, the contractor had signed the contract to get the project. During the project, some factors, such as C8 and C9, were affected by contractual issues. Table 6.9 lists the management strategies for C6.

Table 6.9. Management Strategies Implemented for C6

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	Since the claim rights in the contract are limited, it was aimed to resolve potential problems via mutual agreement by establishing good communication with the owner. In this respect, during the staffing phase, the contractor paid attention to build a project management team consists of people with strong communication skills.	Establishing effective communication facilitated the management of other complexity and uncertainty factors, such as C5, C8, C9, C12, U2.3, for which good communication is essential.
Middle (≈ 50%)	By using the existing approach, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	By using the existing approach, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C7-Lack of Technical Experience:** All of the construction companies that constitute the joint-venture were very experienced in pipeline projects. In particular, the foreign partner was known for its pipeline projects conducted in various parts of the world. Hence, there was no problem arising from a lack of experience over the project duration. Table 6.10 lists the management strategies for C7.

Table 6.10. Management Strategies Implemented for C7

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	Although the partner companies were very experienced, they decided to employ a senior project director who has expertise in pipeline projects so that no problem would be encountered regarding project management. Accordingly, a project director who had previously completed two large natural gas pipeline projects in Turkey has been hired to lead the project.	Since the project director played a critical role in technical and organizational decisions regarding the complexity and uncertainty factors, many factors have been affected by the strategy.
Middle (≈ 50%)	Since the project director has performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	Since the project director has performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C8-Changes in the Project Scope:** Since the scope was clearly defined by the owner at the beginning of the project, there was no significant change in the project route or activities. However, the revisions made in the alignment sheets by the owner at the project initiation stage caused some changes in the scope. Due to these revisions, the total length of the pipeline specified in the contract increased by seven kilometers. At the end of the project, there were disagreements over whether the contractor is responsible for this part. Nonetheless, as the contractor did not have a contractual claim right in this issue, the additional part was included in the scope. Table 6.11 lists the management strategies for C8.

Table 6.11. Management Strategies Implemented for C8

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to alleviate the negative impact of the changes in the alignment sheets, the contractor has decided to optimize the design by recommending revisions during the design verification stage.	Scope changes have increased the complexity in C5. Moreover, revisions planned in the project design made the management of C16 and C17 difficult.
Middle (≈ 50%)	By using the existing approach, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	In order to complete the additional seven kilometers part, some teams in the second section were shifted to the third section.	Shifting the teams to a new location has increased the complexity in C14.

- **C9-Unrealistic Project Targets:** In order to achieve the commitment made by Turkey, the project had to be completed within a certain duration. This duration has been considered as realistic by the contractor during the tender stage. However, after the tender, there was a significant delay in the signing of the contract. Even though milestone dates were postponed based on the effective date, no change was made in the target completion date of the project due to the commitment. Under these circumstances, the target duration of the project was not realistic for the contractor, which caused some time-related disputes in the later stages of the project. On the other hand, the budget and scope targets of the project were reasonable, and they did not cause any serious problems during the project. Table 6.12 lists the management strategies for C9.

Table 6.12. Management Strategies Implemented for C9

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	The contractor was aware that the project was not likely to be completed within the specified duration prior to signing the contract. For this reason, in the beginning, it was decided to increase the resources by reducing the profit margin so that project can be completed on time.	Increasing the resources in the project has increased the complexity in C13 and C14. Furthermore, it made the management of C10, C15, U1.2, and U2.2 difficult.
Middle (≈ 50%)	Despite the increase in resources, the project was still behind schedule due to other delays experienced in the beginning. Since the claim rights of the contractor are limited, it was decided to settle with the owner by negotiations. As a result of long discussions, a three-month additional time was granted to the contractor for the non-essential works of the project. Non-essential works express the activities that do not directly affect the delivery of the gas, such as laying the topsoil, landscaping, and fencing of the site. On the other hand, the initial completion date was still valid for the essential works to ensure the timely delivery of the gas.	Negotiations for the time extension have increased the complexity in C5.
End (≈ 90%)	Since the time-related issues have been resolved, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C10-Unavailability of Resources (Labor, Material, Equipment):** There was a massive requirement for labor and equipment resources in the project. The number of workers was about 2500 at the peak, while the number of heavy equipment in the project was more than 100. In terms of resource availability, it was challenging to find a qualified workforce in accordance with the quality standards of the project. The workers that comply with these standards were increasing their wage demands after a while. Since they did not work in the project for a long time, there was a constant need for a new workforce. The materials of the project were mainly composed of the pipes, which were supplied by the owner. Therefore, the contractor did not experience any problem related to the unavailability of materials. Similarly, there was no issue related to the availability of equipment. However, it was necessary to make a detailed plan as the number of equipment in the project was too high. The contractor encountered some procurement problems at the end of the project due to the production troubles of the Italian valve supplier. Table 6.13 lists the management strategies for C10.

Table 6.13. Management Strategies Implemented for C10

Project Stage	**Strategy**	**Other Factors Affected by the Strategy**
Beginning (≈ 10%)	The qualified workforce requirement of the project was met by the Indian workers who have experience in pipeline projects. The heavy equipment of the project was obtained by the leasing. For the light equipment, agreements were made with suppliers mainly from abroad. These suppliers were requested to report their productions regularly. Furthermore, periodic factory visits were arranged to avoid any delay caused by the procurement.	Hiring qualified workers from India has decreased the complexity in C7 and uncertainty in U2.1, whereas it has increased the complexity in C12. Furthermore, it facilitated the management of C17. On the other hand, precautions related to the suppliers have increased the complexity in C5.
Middle (≈ 50%)	By following the existing procurement plan, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	A project team was sent to Italy to resolve the problems caused by the supplier. As a result of the negotiations, the supplier agreed to provide the valves over another factory.	Negotiations with the supplier have increased the complexity in C5 further.

- **C11-Interactions between the Project Disciplines:** Since the project consisted of linear activities carried out in a wide construction area, interactions between the project disciplines were limited, except for above-ground structures, such as camps, pigging stations, and block valve stations. However, due to overlaps towards the end of the project, interactions increased to some extent. Table 6.14 lists the management strategies for C11.

Table 6.14. Management Strategies Implemented for C11

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	The construction manager was responsible for managing coordination problems both within and across the sections as per the job description. Accordingly, a management organization has been established by the construction manager to coordinate the interactions between the project disciplines.	Ensuring the coordination between the project disciplines has decreased the uncertainty in U2.2. Furthermore, it facilitated the management of C13 and C14.
Middle (≈ 50%)	Since the construction manager has performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	Since the construction manager has performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C12-Cultural Diversity:** Although there was a foreign partner in the joint-venture, they had previously worked together with one of the existing partners in a pipeline project in Turkey. On the other hand, approximately 60% of the project teams were Indian, and 40% were Turkish. However, despite the cultural diversity among project teams, there was no significant problem in this regard. Table 6.15 lists the management strategies for C12.

Table 6.15. Management Strategies Implemented for C12

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	It was aimed to create a comfort zone for the employees through local cuisines and social facilities. However, they should not have gotten the impression that they were parts of different teams. For this reason, collaborative activities were organized to improve the harmony between the project teams.	Increasing the motivation of the project teams has decreased the uncertainty in U2.1 and U2.2.
Middle (≈ 50%)	By using the existing approach, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	By using the existing approach, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C13-Multiple Critical Paths (Parallel Activities):** Due to the nature of the project, there was a linear schedule composed of seven major activity groups that repeated at different locations. However, due to time pressure in the project, the number of activities carried out simultaneously at various points was high. As the project progresses, the number of parallel activities continued to increase to compensate for the delay introduced at the beginning of the project. Table 6.16 lists the management strategies for C13.

Table 6.16. Management Strategies Implemented for C13

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to maintain the workflow and prevent overlaps, activities were planned to move in a natural rhythm. In this respect, teams were encouraged to immediately proceed to the next location when they encounter physical obstacles. With this approach, it was aimed that workers get used to their work more quickly, and thus increase their productivity. Moreover, support teams were provided for the construction of the uncompleted parts in the relocation points.	Moving teams quickly and using support teams have increased the complexity in C14. Moreover, the existence of relocation points made the management of U1.2 difficult since they affect the rental period of the equipment significantly (please see U1.2).
Middle (≈ 50%)	In order to coordinate the growing number of parallel activities in the project, location-based arrangements were made in the schedule.	Coordinating the parallel activities has decreased the uncertainty in U2.2. Furthermore, it facilitated the management of C14.
End (≈ 90%)	By following the existing coordination plan, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C14-Staff and Equipment Mobility:** As a consequence of both the repetitive nature and excessive resource requirement of the project, staff and equipment mobility was too high throughout the project. When the number of teams and parallel activities increased in the later stages of the project, mobility, and thus coordination challenges continued to grow. Table 6.17 lists the management strategies for C14.

Table 6.17. Management Strategies Implemented for C14

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	As explained in C11, the construction manager was responsible for managing coordination problems in the project. Therefore, the management organization established by the construction manager also helped to coordinate the mobility in the construction site.	Coordinating the mobility in the construction site has decreased the uncertainty in U2.2. Furthermore, it facilitated the management of C15.
Middle (≈ 50%)	Since the construction manager has performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	Since the construction manager has performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C15-Physical and Logistic Constraints:** The project involved geographically dispersed construction areas where different physical constraints exist. Since each region has unique conditions, the project teams had to deal with various physical obstacles. In particular, problems were encountered due to weather conditions of the high-altitude points. On the other hand, there were also logistic constraints as the construction was performed in a wide area. For example, though the pipes were supplied by the owner, transporting them to different construction locations was the responsibility of the contractor. The pipes procured from Chinese and Turkish suppliers required specific logistic arrangements. In the middle of the project, the pipes shipping from China were landed at a different port, a far distance from the original port stated in the contract. For this reason, additional logistics difficulties arose in the project. Furthermore, the distance between the main camps and construction locations was increasing as the project progresses. In the later stages of the project, it started to take a longer time to arrive at the construction area, which caused a reduction in effective working time. Thus, the contractor had to take different measures to cope with logistic problems throughout the project. Table 6.18 lists the management strategies for C15.

Table 6.18. Management Strategies Implemented for C15

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to avoid physical constraints, seasonal conditions were taken into account when planning the works. Accordingly, the construction activities at the high-altitude points were scheduled to be performed between April and September. On the other hand, in order to minimize logistical problems, the fly camps were utilized in addition to the main and intermediate camps. Furthermore, since each pipe at the stockyard had to be positioned on a specific location, their GPS coordinates were monitored through pipe tracking software.	Considering the seasonal conditions in construction planning facilitated the management of U1.1. On the other hand, precautions related to the logistic constraints facilitated the management of C14.
Middle (≈ 50%)	The contractor had the right to request a change order in case the pipes were landed at a different port. Accordingly, additional transportation expenses were covered with the change order issued by the owner.	Discussions for the issuance of the change order in the project have increased the complexity in C5.
End (≈ 90%)	In one of the construction locations, when the distance became too far from the main camp, the related teams were moved to a hotel in a nearby town. In order to get the approval of the owner, the contractor took additional safety precautions in the hotel. As a result, the time spent to arrive at the construction area reduced considerably with this arrangement.	Moving the teams to a hotel made the management of U2.2 difficult. Moreover, with the inspections made by the owner to ensure the hotel is suitable in terms of physical space or fire systems, the complexity in C5 has increased further.

- **C16-Technological Novelty of the Project:** There was no requirement for a new technology or construction technique in the project. However, the operations of the selected construction method had to be performed very carefully. According to this method, the pipes were laying as a platform to speed up the construction. Following the trench excavation, the pipes were aligning head to head. After the welding, x-ray, and coating processes on the ground, they were being placed in the trench as a platform using side booms.

Despite the technical difficulties, no problem was encountered regarding the construction process of the project. Table 6.19 lists the management strategies for C16.

Table 6.19. Management Strategies Implemented for C16

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	Due to the technical difficulty of the construction operations, experienced supervisors and side boom operators were appointed in the project.	Using experienced construction teams has decreased the complexity in C7 and uncertainty in U2.1.
Middle (≈ 50%)	By keeping the existing staffing policy, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	By keeping the existing staffing policy, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **C17-Originality of the Project Design:** Since the design was prepared by the owner, the contractor was responsible for the verification only. As it was quite similar to the design of the previous pipeline projects, the contractor did not experience any problem arising from the originality of the project design. However, as explained in C3 and C8, changes made in the alignment sheets in the beginning and problems with the design verification teams after the coup attempt caused some time and cost overruns concerning the design. Table 6.20 lists the management strategies for C17.

Table 6.20. Management Strategies Implemented for C17

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to compensate for design-related losses, with the approval of the owner, some revisions were made for the locations determined to be overdesigned.	Discussions for the design revisions have increased the complexity in C5. Moreover, changes in the design made the management of C16 difficult when it affected the construction method.
Middle (≈ 50%)	By keeping the existing value engineering perspective during the design verification, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	By keeping the existing value engineering perspective during the design verification, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **U1.1-Weather Conditions:** Due to the direct interactions of the project with the external environment, uncertainty in weather conditions was an important factor that could affect productivity. As the project covered a very large area, the weather conditions varied from region to region. In the same season, some locations were covered with snow, whereas others had warm spring weather. There were also some areas with flood risks. Therefore, seasonal uncertainties have occasionally affected the project. Furthermore, delays at the beginning of the project canceled the initial construction plan, which has been developed according to the seasonal weather conditions. For instance, the part scheduled to be constructed between April and September due to harsh winter conditions did not start as planned because project teams could not arrive in this region on time. However, the impact of uncertainties related to the weather conditions reduced in the later stages since the project was adapted to the external conditions better. Table 6.21 lists the management strategies for U1.1.

Table 6.21. Management Strategies Implemented for U1.1

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	A schedule that can reflect the impact of uncertainties related to the weather conditions on productivity has been developed. Accordingly, for the regions that the project is passing through, meteorological data were analyzed to determine the number of non-working days caused by the weather conditions. Then, these days were incorporated into the project calendar so that a more realistic schedule could be developed based on past data.	Developing a schedule that reflects the seasonal uncertainties facilitated the management of C9 (in terms of duration targets) and C15.

Table 6.21. (Cont'd) Management Strategies Implemented for U1.1

Project Stage	Strategy	Other Factors Affected by the Strategy
Middle (≈ 50%)	Due to the nature of the pipeline construction, activities at different locations were not affecting each other. For this reason, it was possible to shift the project teams to more appropriate locations when seasonal conditions prevent construction. In order to complete the project on time, the part planned to be constructed in the summer period, but could not be arrived on time, was skipped to be built one year later. The schedule was revised accordingly, and the teams were shifted to a location where the weather conditions were more favorable.	Shifting the teams to a different location has increased the complexity in C14. Furthermore, it made the management of C15 difficult.
End (≈ 90%)	Since there was no significant deviation in the revised plan, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **U1.2-Rental Cost of the Equipment:** Since most of the heavy equipment was obtained by the leasing, their rental cost was one of the most critical expense items in the project. The most significant uncertainty concerning the rental cost was the fluctuations in the market. Due to unexpected increases, the contractor could have suffered serious losses in the project. Nonetheless, although there were increases in the rental cost throughout the project, they were usually dependent upon the dollar exchange rate. Since the contract was dollar-based, the contractor was not affected by these increases significantly. Another uncertainty related to the equipment cost was the rental period. The contractor had to have returned the equipment in the shortest possible time to minimize their cost. However, the equipment usage time in the project was linked to the other uncertainties related to productivity. In particular, the relocation points mentioned in C13 had begun to influence the cost negatively. In relation to lower efficiency at these points, the equipment cost had been becoming approximately 12 times higher than the other parts of the project. The most important reason for the emergence of relocation points was physical obstacles. Since the obstacles have been identified initially, the number of relocation points in the project was estimated in advance. However, as the project progresses, their number exceeded the predictions because project teams were taking the initiative to bypass even the smallest obstacles to move faster. Therefore, uncertainty in the rental cost of the equipment, which was mainly affected by the existence of the relocation points, continued to be effective in the project until the factors influencing the rental period were taken under control in the later stages. Table 6.22 lists the management strategies for U1.2.

Table 6.22. Management Strategies Implemented for U1.2

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	Since it was not possible to take a proactive measure against the fluctuations in the market, it was aimed to keep the rental period under control to manage the uncertainties regarding the rental prices. In this regard, detailed equipment planning was prepared at the beginning of the project, and the rental period of the related equipment was estimated. In order to return the equipment in the shortest possible time, a target number of joints was determined for each team based on the 20000 welding points in the project.	Estimating the number of equipment to be used in the project with detailed planning facilitated the management of C10 and C13.
Middle (≈ 50%)	In order to reduce the uncertainty arising from the number of relocation points, some additional measures were taken. At the beginning of the project, teams were allowed to proceed with the next location when they encounter obstacles. However, since their priority was to reach the target number of joints and maintain the workflow, the number of relocation points increased considerably. For this reason, in the later stages of the project, it was decided that bypassing a point would only be possible with the approval of the construction manager. In this way, except for the major physical obstacles, relocation points were restricted.	Restricting the relocation points has decreased the complexity in C14.
End (≈ 90%)	By keeping the existing restrictions, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **U1.3-Force Majeure Events:** The contractor has established a large project management organization by significant investment to carry out a massive mega construction project. Despite its low probability, the impact of a force majeure event would have been devastating for the contractor. For this reason, force majeure events were considered as an uncertainty factor at the beginning of the project. However, the project was completed without such an event. Table 6.23 lists the management strategies for U1.3.

Table 6.23. Management Strategies Implemented for U1.3

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	Since the project was undertaken by accepting the risk of force majeure events, it was decided to follow the detailed procedure described in the contract if such an event happens. Therefore, no additional strategy has been developed in this regard.	N/A
Middle (≈ 50%)	By using the existing approach, the same strategy continued to be implemented.	N/A
End (≈ 90%)	By using the existing approach, the same strategy continued to be implemented.	N/A

- **U2.1-Quality Performance of the Project:** The quality standards set by the owner were at the highest level in the project. There were very long checklists regarding the criteria that must be met even for the small construction units like camps. Moreover, the acceptable margin of error for the cracks in the welding of pipes, as well as the bending during the placement, was very low. The project also includes a 25-year latent defect period, which was above the usual standards in Turkey. Therefore, repair and rework related to the imperfect productions that do not meet the quality standards could have caused significant time and cost overruns in the project. The uncertainty regarding the quality performance of the project was initially high due to vagueness about the performance of the construction teams. However, as the project progresses, the uncertainty was decreased since the performance data of the teams became clear. The most important problem concerning the quality performance was the high defect rates arose in the middle of the project due to an unknown issue in the welding gas. During that time, productivity decreased due to the repair in welding that does not comply with the quality standards. However, there was no significant problem regarding the quality tests of the completed pipes throughout the project. Table 6.24 lists the management strategies for U2.1.

Table 6.24. Management Strategies Implemented for U2.1

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to reduce the uncertainty related to the quality performance of the project, some measures were taken. Although Turkish partners of the joint-venture worked with the subcontractors in most of their previous projects, the contractor did not use any subcontractor in this project to prevent the possible performance risks and control the workers better. Instead, workers were recruited under the management structure of the contractor following a detailed training program. Since the welders had to be approved by the owner, particular attention was given to their training, and they were certificated by the contractor before hiring.	Using a qualified and trained workforce has decreased the complexity in C7.
Middle (≈ 50%)	Since the issue in the welding gas could not be resolved by the project team, a specialist was brought from Germany with the request of the owner.	Discussions during the process of resolving the problem have increased the complexity in C5.
End (≈ 90%)	Since there was no additional issue concerning quality performance, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **U2.2-Health and Safety Performance of the Project:** Similar to the quality, the occupational health and safety standards set by the owner were extremely high in the project. For example, it was mandatory to have emergency medical services on the construction site for possible accidents. There were also serious health and safety precautions in the camps. Moreover, due to the nature of linear projects, the project teams had to be transported long distances from the camps every day. The possible traffic accidents during the transportation of the teams were considered the most critical health and safety risk of the project by the owner. In this respect, the contractor was obliged to equip all cars with the necessary safety equipment like roll bars, provide advanced driving training for the drivers, and use the vehicles only between certain hours. Therefore, administrative sanctions related to the health and safety violations could have caused significant time and cost overruns in the project. As in the case of quality, there was a high uncertainty regarding the health and safety performance of the project teams initially. However, as the project progresses, vagueness about their performance was decreased. The advanced healthy and safety measures taken in the project enabled the contractor to complete five million working hours without a lost-time injury. Table 6.25 lists the management strategies for U2.2.

Table 6.25. Management Strategies Implemented for U2.2

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to reduce the uncertainty related to the health and safety performance of the project, a large number of safety supervisors have been appointed in the project. They were responsible for providing regular training and certification programs to the project teams.	Fulfilling the requirements of the owner regarding the health and safety precautions has decreased the complexity in C5.
Middle (≈ 50%)	Since the safety supervisors have performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	Since the safety supervisors have performed well, no new strategy has been implemented for this factor.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

- **U2.3-Public Opposition:** The project was passing through some towns and villages on its route. The right of way for these parts had been taken by the owner, and the local people had been informed about the project previously. For this reason, the uncertainty about the public opposition was low.

Nonetheless, the contractor was still required to establish good communication with the local people affected by the project. If it had caused a social and economic impact on the public, there would have been a negative attitude towards the continuation of the project. However, thanks to the measures taken, no problem was experienced with the local people. Table 6.26 lists the management strategies for U2.3.

Table 6.26. Management Strategies Implemented for U2.3

Project Stage	Strategy	Other Factors Affected by the Strategy
Beginning (≈ 10%)	In order to reduce the uncertainty related to the public opposition, various activities have been organized through the public relations department. Within the scope of the livelihood restoration plan, regular meetings were conducted in the villages to inform the local people about the progress of the project as well as eliminate their project-related losses.	Meetings with the public have increased the complexity in C5.
Middle (≈ 50%)	By following the existing public relations plan, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.
End (≈ 90%)	By following the existing public relations plan, the same strategy continued to be implemented.	Since a new strategy was not implemented, there was no additional factor affected at this stage.

6.2.2.2 Rating the Risk Sources

Following the identification of the risk sources with the project manager, a rating exercise was conducted for different stages of the project. There were three main issues that need to be considered by the manager while scoring a factor. First of all, its magnitude in the project during the stage of assessment should be determined. Second, the direct impact of the strategy implemented for this factor should be reflected in the rating. Third, the indirect impact of the other strategies affecting this factor should also be taken into account. For example, while rating C7, strategies developed for C10, C16, and U2.1 were also considered since they influenced this factor. Consequently, instead of an isolated analysis, IRAP ensured to assess complexity and uncertainty factors within a network setting.

Based on this procedure, all risk sources were rated on a five-point Likert scale by considering their level at the beginning, middle, and end of the project. Besides these three stages, another rating was provided for the planning stage of the project without considering any strategy. The complexity and uncertainty scores assigned for these stages are presented in Table 6.27.

Table 6.27. Scores of the Risk Sources for Different Stages of the Project

ID	Planning (No Strategy)	Beginning (≈ 10%)	Middle (≈ 50%)	End (≈ 90%)
C1	5	5	5	5
C2	2	2	1	1
C3	4	3	1	1
C4	2	1	1	1
C5	5	3	4	4
C6	4	4	4	3
C7	2	1	1	1
C8	2	2	2	3
C9	4	3	1	1
C10	3	2	2	3
C11	2	2	2	3
C12	3	2	2	2
C13	2	2	4	4
C14	4	4	5	5
C15	5	4	5	4
C16	2	1	1	1
C17	2	2	1	1
U1.1	4	3	2	1
U1.2	3	3	3	1
U1.3	2	2	1	1
U2.1	5	4	3	2
U2.2	5	4	2	1
U2.3	2	2	2	1

By multiplying the scores given in Table 6.27 with the corresponding weights of the ANP model, assessment scores were obtained for each risk factor. The following section exemplifies the details of the calculation procedure.

6.2.2.3 Calculation Procedure

This section clarifies the steps of the ANP-based risk score calculations. According to the ANP model, the score of each risk factor is estimated over three complexity and two uncertainty categories. Therefore, the first step should be determining the category scores through corresponding complexity and uncertainty factors. To illustrate this operation, Figure 6.1 demonstrates the calculation of the environmental complexity at the beginning of the project using the scores of the related complexity factors given in Table 6.27 and their weights given in Table 5.8.

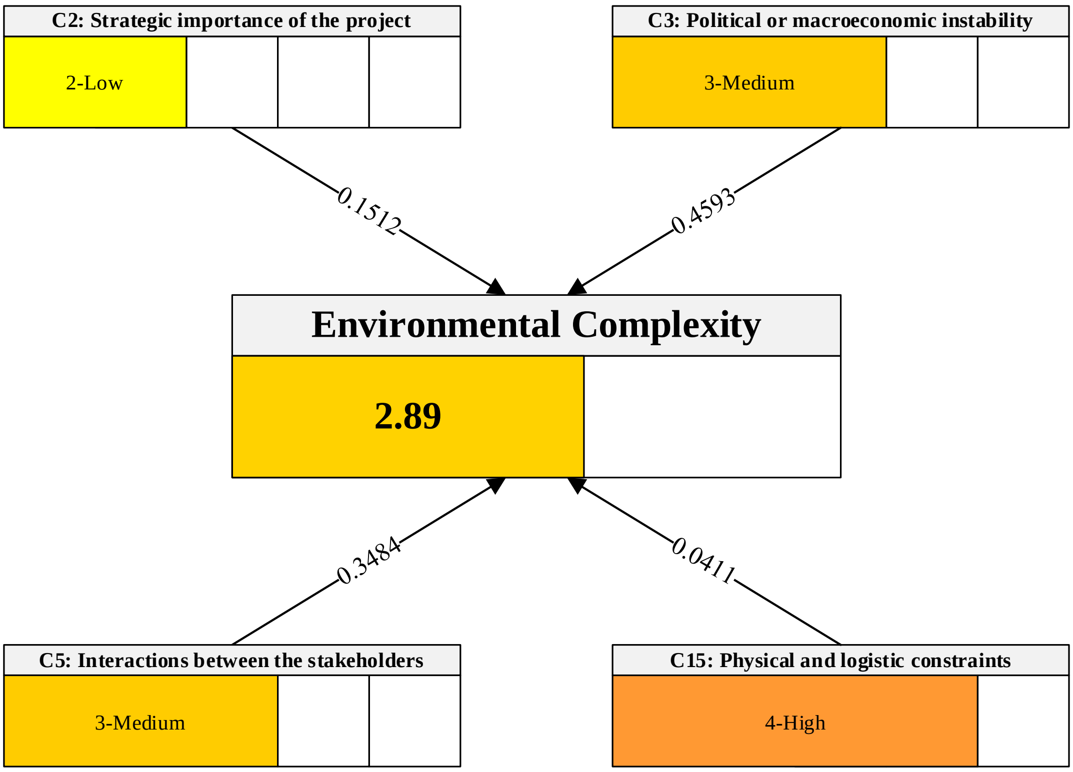


Figure 6.1. Environmental Complexity at the Beginning of the Project

In Figure 6.1, scores belong to C2, C3, C5, and C15 were multiplied with the weights written on the arrows. Then, the obtained results were summed to determine the environmental complexity score (2.89). The same operation should be repeated for other complexity and uncertainty categories to calculate their scores as well. The next step should be determining the scores of each risk factor over the five categories. In this respect, Figure 6.2 exemplifies the calculation of the contractual risks (R3) at the beginning of the project.

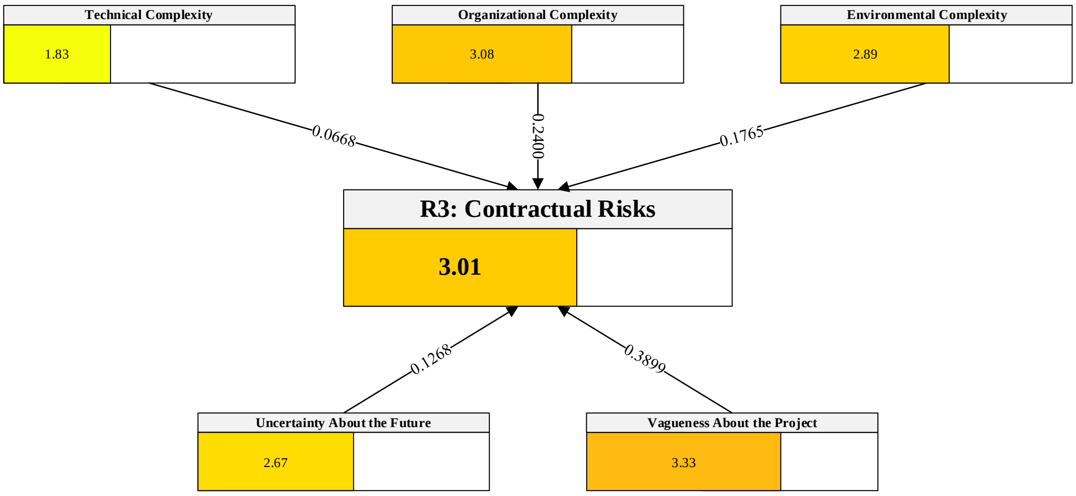


Figure 6.2. Contractual Risks at the Beginning of the Project

In Figure 6.2, scores determined for the three complexity and two uncertainty categories were multiplied with their total weights written on the arrows to calculate R3 (3.01). The weight of each category was obtained by the summation of the related factor weights given in Table 5.14 for R3. The same category scores should also be multiplied with the weights of other risk factors so that all risk scores can be determined. The final step of the calculations should be determining the overall risk of the project by multiplying the score of each risk factor with the corresponding priority given in Table 5.3 and summing up the results. To illustrate this step, Figure 6.3 demonstrates the calculation of the overall risk score (2.86) at the beginning of the project.

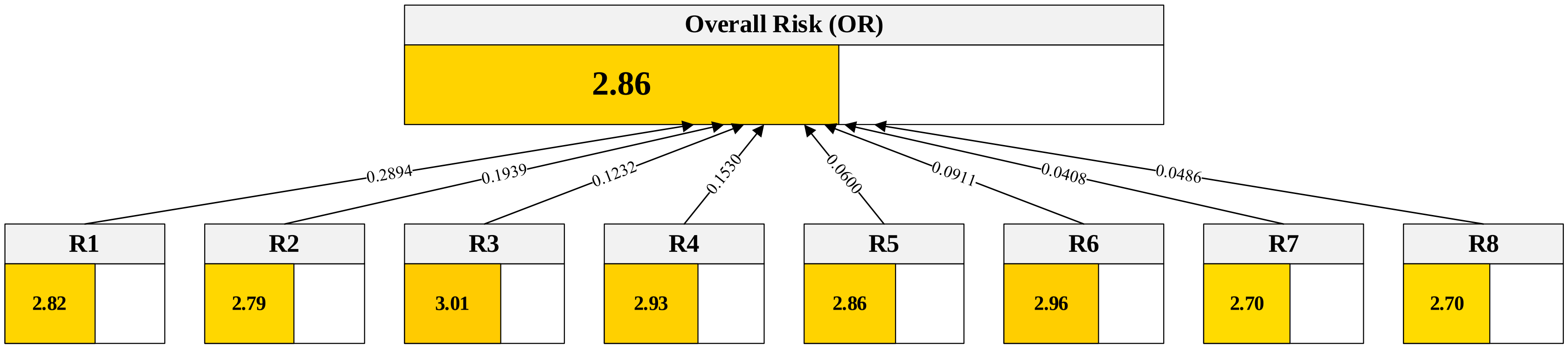


Figure 6.3. Overall Risk at the Beginning of the Project

6.2.2.4 Risk Assessment Scores

Based on the calculation procedure explained in the previous section, risk assessment scores of all factors were determined for four different stages of the project. Table 6.28 presents the risk assessment scores calculated over the ratings given in Table 6.27.

Table 6.28. Risk Assessment Scores for Different Stages of the Project

ID	Planning (No Strategy)	Beginning (≈ 10%)	Middle (≈ 50%)	End (≈ 90%)
R1	3.47	2.82	2.22	1.72
R2	3.35	2.79	2.26	1.80
R3	3.63	3.01	2.42	1.96
R4	3.48	2.93	2.40	1.97
R5	3.43	2.86	2.30	1.86
R6	3.49	2.96	2.45	2.02
R7	3.26	2.70	2.15	1.77
R8	3.27	2.70	2.14	1.76
OR	3.45	2.86	2.30	1.84

According to Table 6.28, contractual risks (R3) was the most significant risk factor during the planning stage of the project. Due to the unfavorable contract clauses, explained in Section 6.2.2.1, R3 was anticipated as the most crucial risk factor by the project manager at the beginning of the project. Hence, the result calculated by the model aligned with the perception of the manager. Project management and organization risks (R6) was determined as the second-highest risk factor, followed closely by owner-related risks (R4) and country-related political and economic risks (R1). These findings were also considered reliable. According to the project manager, the governance and coordination of the geographically dispersed project teams was the most challenging part of the project. Similarly, the owner was evaluated as an important risk source because of not only the strict contractual obligations but also extremely high standards set in the project. Furthermore, the volatile environment caused by the coup attempt at the beginning of the project has increased the R1. Even though R3 has been among the top three risk factors throughout the project, its impact was mitigated after the amendment made for the non-essential works discussed in Section 6.2.2.1. Therefore, R6 became the most significant risk factor after the middle of the project since the coordination issues continued to be a challenge over the course of the project. On the other hand, construction-related/technological risks (R7) and design risks (R8) were the least significant risk factors for most of the stages. According to the project manager, the project was not very challenging in terms of construction operations since the same activity types were repeated at different locations. Similarly, except for the changes in the alignment sheets at the beginning of the project, design-related issues were not considered a critical risk factor. Hence, the calculations of the model reflected the thoughts of the project manager. Apart from these two factors, R1 became the least significant risk factor at the last stage as the impact of the country-related problems has reduced towards the completion of the project. Figure 6.4 depicts the changes in the risk assessment scores at different stages of the project.

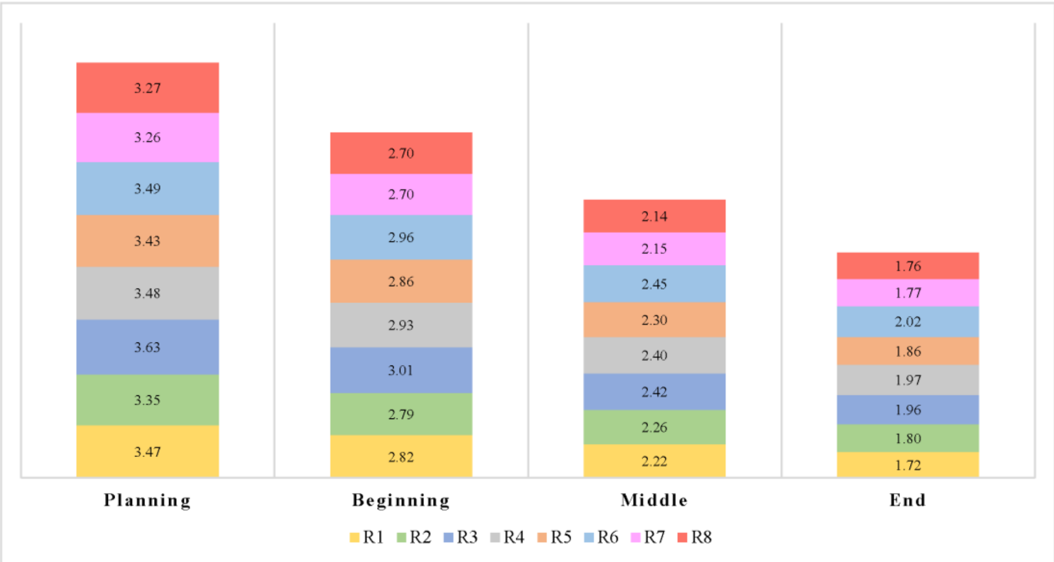


Figure 6.4. Changes in the Risk Assessment Scores

Figure 6.4 demonstrates that all risk factors, as well as the overall risk, have decreased throughout the project. The results also revealed the critical role of management strategies in reducing project risks. For instance, strategies implemented at the beginning of the project enabled more than a 17% reduction in the overall risk. Nonetheless, the changes in the risk scores also depend on the factors affecting the magnitude of the source parameters. In order to demonstrate the variations in the risk sources, scores calculated for three complexity and two uncertainty categories at the beginning, middle, and end of the project are presented in Table 6.29.

Table 6.29. Category Scores for Different Stages of the Project

Category	**Beginning (≈ 10%)**	**Middle (≈ 50%)**	**End (≈ 90%)**
Technical Complexity	1.83	1.71	2.07
Organizational Complexity	3.08	3.12	3.31
Environmental Complexity	2.89	2.21	2.17
Uncertainty about the Future	2.67	2.00	1.00
Vagueness about the Project	3.33	2.33	1.33

According to the results given in Table 6.29, categories displayed different behaviors in terms of variations in the scores. Despite the existence of management strategies, organizational complexity continued to increase throughout the project. However, the results should not imply that the management strategies used in the project were ineffective. On the contrary, they helped keep the high organizational complexity of the project within an acceptable level. In contrast to organizational complexity, environmental complexity showed a declining trend over time. In terms of technical complexity, variations were inconsistent. Although there was a slight decrease until the middle of the project, it started to climb thereafter. On the other hand, the level of uncertainty reduced continuously over the project duration. The decrease in vagueness about the project might be achieved by closing the information gap over time. Similarly, the impact of uncertainty about the future can be expected to decrease as the project progresses. For example, an increase in the rental cost of the equipment at the end of the project could be less significant as compared to the initial stages. Furthermore, management strategies contributed to decreasing the level of uncertainty in the project for both categories. Figure 6.5 visualizes the changes in the category scores and overall risk at different stages of the project.

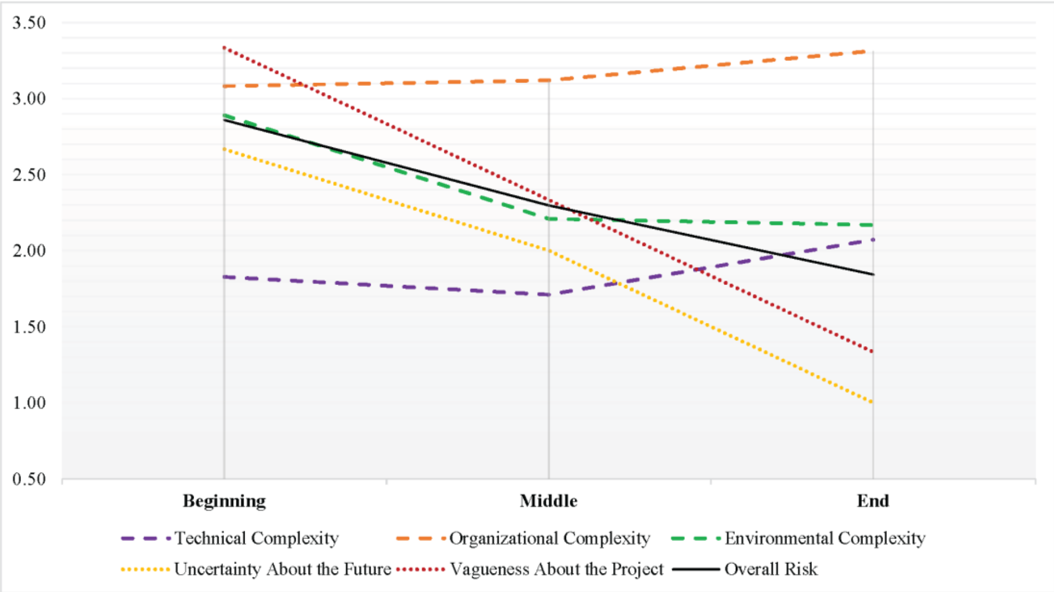


Figure 6.5. Changes in the Category Scores

Figure 6.5 points out that the risk reduction in this project was more closely associated with lowering the level of uncertainty. Despite the decreasing trend in the risk level of the case project, other mega construction projects may not show the same behavior. The emergence of a critical risk source during the project may cause sudden increases in the risk level. Similarly, a strategy developed for a risk factor may increase the risk level in other factors. For instance, hiring a subcontract to reduce the technical risks in the project may amplify the coordination-related risks. Therefore, both the risk sources and the impact of management strategies should be assessed periodically, as promoted by IRAP.

6.2.3 Summary of the Findings from the Demonstrative Case Study

As a result, the demonstrative case study revealed how IRAP and the ANP-based quantitative model could be used in practice to assess the risks of a mega construction project. The performance of the proposed risk assessment approach found promising in terms of unveiling the risk sources in the project and reflecting the risk perception of the project manager. Thus, IRAP has the potential to improve the risk management performance of mega construction projects. The following are the main takeaways from the demonstrative case study:

- The main benefit of the proposed risk assessment approach is that it integrates complexity-based thinking into risk management. While the traditional risk assessment techniques are based on estimating the probability and impact of unknowns, IRAP promotes to analyze the static and dynamic complexity factors, together with the uncertainty factors, in the project as potential risk sources. It facilitates the exploration of all possible risk causes in the assessment process.
- Another important aspect of IRAP is that management strategies are engaged in the risk assessment process. In traditional approaches, identification, analysis, and response are the successive phases of risk management. However, IRAP integrates the response strategies into both the identification and analysis of the risk sources. During the identification phase, they provide a feedback loop to uncover new risk sources resulting from their impact on the project. They are also taken into account during the analysis phase as their effects are reflected while rating the magnitude of the identified risk factors. Thus, management strategies constitute the cornerstone of the network-based approach in IRAP.
- IRAP also provides a practical risk monitoring approach for ongoing projects. It facilitates to assess the risk levels throughout the different stages of the project and evaluate the fluctuations in the risk factors over the source

parameters. Thus, the reasons for the increase in the risk level during a specific period of the project could be identified using IRAP.

- Although IRAP principally serves for risk assessment during the project lifecycle, it may also be used for other purposes. For example, as it can simulate the impact of different strategies on risk levels, scenario analysis may be performed with IRAP to select the most appropriate risk management strategies. Moreover, within a database setting, it may help to record the lessons-learned for the forthcoming projects. However, further studies are needed to test the validity of IRAP in other applications.

CHAPTER 7

CONCLUSIONS

Megaprojects are of great importance due to their potential to contribute to the development and welfare of society. However, the challenges arising from their characteristic features often lead to poor project performance. Although complexity and risk inherently exist in megaprojects, project management literature lacks a structured risk assessment process to integrate them. Moreover, there is not a consensus about the nature of their relationship. Based on this gap, four research objectives were set, and a research design composed of three phases was employed to answer the research questions.

In the first phase, an exploratory study based on mixed-methods research was conducted to analyze data acquired through interviews with 18 participants from 11 mega construction projects carried out by the Turkish contractors. The quantitative analysis uncovered the relationship between complexity and risk by showing that some complexity factors were more closely associated with the change in the scores of some risk factors. The qualitative analysis, on the other hand, provided some evidence about the nature of this relationship by exposing their links mediated by the uncertainty and management strategies. The individual results of the quantitative and qualitative parts served to answer the first research question by explaining what kind of relationship exists between complexity and risk factors in mega construction projects. In order to shed light on the implications of this relationship in terms of developing an integrated risk management approach for mega construction projects, and thus address the second research question, an Integrated Risk Assessment Process (IRAP) was proposed by consolidating the findings of the quantitative and qualitative parts. Then, IRAP was operationalized by developing an Analytic Network Process (ANP) model. The weights of the parameters in the ANP model were assigned through a two-round Delphi study conducted with five experts. The questionnaire data obtained via an interactive data collection tool in the first round were refined through an expert panel in the second round. The resulting analytical model helped to answer the third research question by showing how the risks of mega construction projects can be quantified based on the integrated risk management approach. Finally, validation studies were conducted to test both risk quantification performance of the ANP model with the risk assessment of 11 mega construction projects and the applicability of the ANP model and IRAP with a demonstrative case study. These studies enabled the fourth research questions to be addressed by demonstrating how the integrated risk management approach can be utilized in practice for managing risk-related factors of mega construction projects.

In conclusion, a holistic framework linking risk, uncertainty, complexity, and management strategies concepts, IRAP that guides decision-makers to incorporate complexity into risk assessment, and an ANP-based model that quantifies the risks considering the aforementioned concepts were the main outputs of this thesis. Studies conducted to test the validity of these outputs revealed the potential of the proposed risk assessment approach in risk management and monitoring of mega construction projects.

The following sections present the summary of the main findings from the research, as well as the contributions, the limitations, and the recommendations for future research.

7.1 Summary of the Findings

The main findings of the research are summarized as follows:

- **About the complexity, risk, and their interactions in mega construction projects:** The quantitative findings from the first phase of the research showed that "interactions between the project disciplines," "size of the project," "interactions between the stakeholders," "strategic importance of the project," and "multiple critical paths (parallel activities)" were the most significant complexity factors that appeared in more than half of the investigated megaprojects. There were also context-dependent complexity factors. “Changes in the project scope” and “political or macroeconomic instability” were the notable factors for the projects more vulnerable to scope creep and country-related problems. On the other hand, “unrealistic project targets,” “inadequacy of the contract,” and “cultural diversity” were the least significant complexity factors for the projects in the data set. Complexity scores demonstrated that practitioners of mega construction projects should account for various technical, organizational, environmental complexity sources depending upon the characteristics of their projects. Furthermore, from the quantitative analysis of risk factors, it was found that predicting the impact of “country-related political and economic risks” and “owner-related risks” was difficult. While “project management and organization risks” and “construction-related/technological” risks had the lowest rate of change in the risk impact scores, the latter was the only factor with a negative variation, which implied that the impact of technical risks might be overestimated at the beginning of the megaprojects. The results also revealed that “design risks” might be context-dependent. Their effects may be higher or lower than expected, depending on the project conditions. Interpreting the complexity and risk scores together showed that there might be a correlation between the specific complexity and risk factors. The unpredictability of the external risk factors, such as political, economic, and financial, were more closely associated with high environmental complexity. Similarly, it was observed that a high organizational complexity makes it more difficult to predict the impact of managerial and organizational risks. Moreover, the results revealed that technical complexity is highly effective for most of the risk factors, and reducing it might facilitate predicting the impact of the construction-related technical risks. Consequently, the numerical analysis performed to quantify the relationship between complexity and risk demonstrated that a high level of complexity in some categories might make it more difficult to predict the impact of specific risk factors in mega construction projects. Following the quantitative part, the qualitative analysis of the interview transcripts further confirmed that complexity affects the emergence of risk events. Although the main focus of this part was exploring the relationship between complexity and risk, the conceptual framework developed through the thematic analysis revealed that uncertainty and management strategies are the other themes essential to conceptualize this relationship. Whereas uncertainty is another risk source, management strategies may affect the way complexity and uncertainty create the risk. Furthermore, strategies developed to manage risk sources can result in additional uncertainty and complexity, which in turn can lead to new risks, known as secondary risks. Thus, there could be two-way interactions between complexity and risk with the inclusion of uncertainty and management strategies. The findings from the qualitative analysis revealed that the multi-level and dynamic interactions between these four concepts might cause significant problems for practitioners to predict the risks in mega construction projects.

- **About integration of complexity into the risk assessment process of mega construction projects:** Merging and interpreting the findings from the quantitative and qualitative analysis suggested that complexity should be considered during the risk assessment process to analyze the risks of mega construction projects more realistically. Based on this implication, an integrated approach, IRAP, was proposed to account for the links between complexity, uncertainty, management strategies, and risk concepts during the risk assessment. Besides the uncertainty, IRAP incorporates complexity into the risk assessment process of mega construction projects as a potential risk source. Then, management strategies are formulated for the identified complexity and uncertainty factors. Since they may trigger the emergence of secondary risks, IRAP includes a feedback loop to identify new risk sources caused by the implemented strategies. As a consequence of this process, a network that links risk-related factors is developed. With the analysis of this network, extra precautions are taken to improve the risk management performance of the project. Since the new strategies may introduce additional risks into the project system, identification of the risk sources is repeated through the feedback loop. As a result, IRAP promotes an iterative process to identify, analyze, and manage the risks of mega construction projects based on the network of risk-related factors.

- **About risk quantification in mega construction projects:** In the next phase, an ANP model was developed to put IRAP into practice. The model comprised the links between the main concepts of IRAP for a network-based analysis. The Delphi study conducted to derive the weights of the analytical model provided more insights into the relationships among risk-related concepts. Based on the pairwise comparisons in the 11 comparison sets, five experts determined the most significant parameters for the risks of mega construction projects. According to the comparisons between risk factors in the first set, “country-related political and economic risks” and “financial risks” were considered the most important risk factors in terms of their contribution to the overall risk. In contrast to the external risks, the technical risks, including “construction-related/technological risks” and “design risks,” were evaluated as less significant by the experts. Comparisons of two uncertainty categories in the second set revealed that “uncertainty about the future” was more influential for the aforementioned external risks. On the other hand, “vagueness about the project” was more closely associated with the technical risks listed above besides the “contractual risks.” A similar comparison was made with the complexity categories in the third set. Accordingly, “environmental complexity” was more significant for the external risk factors, while “technical complexity” was considered more influential for the technical risks. Moreover, “organizational complexity” had the highest priority weight for “project management and organization risks.” These results showed a good alignment with the numerical analysis performed for the 11 mega construction projects in the first phase to quantify the relationship between complexity and risk. Although the selections of the experts did not match with the numerical analysis for the remaining three risk factors, both results confirmed the correlation between specific complexity and risk factors. The next three sets were related to the comparisons of the complexity factors belong to three categories. These results demonstrated that “changes in the project scope,” “size of the project,” and “political or macroeconomic instability” were considered the most significant factors for technical, organizational, and environmental categories, respectively. On the other hand, “technological novelty of the project” and “originality of the project design” in the technical category, “cultural diversity” and “staff and equipment mobility” in the organizational category, and “logistic constraints” in the environmental category were the least significant complexity factors. The subsequent three comparison sets were related to management strategies. First, the effectiveness of the two strategy types on the risk factors was evaluated. Accordingly, the “flexibility” was a more effective strategy for the external risk factors, whereas the “control” was selected as more suitable for the risk factors pertains to the organizational and technical issues. On the other hand, they had an equal weight for the risks related to the owner. The results from all risk factors indicated that two strategies should be implemented in balance for the mega construction projects. According to the next comparison set, uncertainty categories were affected by two strategies differently. While the “control” strategy was thought more effective for “vagueness about the project,” the “flexibility” strategy was selected as a better strategy for “uncertainty about the future.” A similar comparison was made for the complexity categories in the next set. Although “environmental complexity” was the most significant risk source for both strategies, its impact reduced considerably under the “flexibility” strategy. In the last two sets, the experts compared the clusters in the model. The first comparison showed that the weights of the complexity and uncertainty clusters were almost equal in terms of their contributions to risk factors. This result supported the central argument of this research that complexity should be considered in the risk assessment process. On the other hand, the weight of the management strategies was about 10%, which shows that they contribute to the emergence of secondary risks to some extent. Finally, according to the last comparison set, complexity and uncertainty had equal weights as the source of secondary risks. In addition to the local priorities in the 11 comparison sets, global priorities obtained from the supermatrix calculations revealed that "political or macroeconomic instability," "interactions between the stakeholders," and "size of the project" were the most significant complexity factors for the overall risk of a mega construction project. In terms of the category weights, the ranking was determined as "uncertainty about the future," "vagueness about the project," "environmental complexity," "organizational complexity," and "technical complexity." However, it should be noted that the order of the parameters was different for each risk factor.

- **About the validity of the proposed risk assessment approach:** Following the determination of the risk weights, the risk quantification performance of the ANP model was tested through the data available for 11 mega construction projects. According to the test conducted for the individual risk factors, the model showed superior performance for "design risks," "contractual risks," "procurement risks," and "financial risks" with an error rate of less than 10%. However, the prediction error was around 20% for "project management and organization risks," "construction-related/technological risks," "owner-related risks," and "country-related political and economic risks." The relatively poor performance of the model in some risk factors could be explained by the fact that the actual risk data that determine the accuracy of the model represent the viewpoint of the contractors only. For this reason, there might be some risk factors that were over-scored, such as owner risks, or under-scored, such as project management risks. In order to balance the impact of these risk factors, an additional test was performed based on the overall risk score of all projects. According to this test, the prediction error of the model was less than 10% for the majority of the projects. Moreover, the mean absolute percentage error of all projects was calculated as 8.70%. Although these findings revealed the potential of the ANP model in quantifying the risks of mega construction projects, due to the limitations involved in the testing procedure, further analysis was required. In this respect, a demonstrative case study was carried out to test both the performance of the ANP model and the applicability of IRAP. After a detailed analysis of complexity and uncertainty factors, risks of a mega pipeline project were calculated according to the management strategies implemented at the beginning, middle, and end of the project. An additional assessment was performed for the planning stage of the project without considering the impact of the strategies implemented for the risk sources. Findings from the case study revealed that the risk scores calculated for different stages of the project reflected the risk perception of the project manager with high accuracy. Moreover, IRAP facilitated identifying all static and dynamic complexity factors, together with the uncertainty factors, as potential risk sources of the project. The case study also demonstrated the critical role of management strategies in the risk assessment process. Strategies implemented in the beginning helped to reduce the overall risk score of the project calculated at the planning stage by more than 17%. The management strategies also had an impact on the emergence of new risk sources during the identification stage. Another important finding from the demonstrative case study was the potential of IRAP in risk monitoring. Although the risk factors of the investigated case have decreased throughout the project, there were increases in some risk sources. While "organizational complexity" showed an increasing trend over the project duration, "technical complexity" started to increase after the middle of the project. On the other hand, the level of "environmental complexity," "uncertainty about the future," and "vagueness about the project" continually reduced throughout the project. In particular, lowering the level of uncertainty was critical in reducing the risks of the case project. These findings indicated that IRAP could also effectively detect the sources that cause unexpected fluctuations in the risk level if risks are assessed periodically at different stages of the project. As a result, the demonstrative case study revealed the contributions of IRAP and the ANP-based quantitative model in terms of managing and monitoring the risks in mega construction projects.

7.2 Contributions of the Research

This research can advance the body of knowledge in the construction project management field with its conceptual, empirical, methodological, and practical contributions, summarized below.

In terms of conceptual contributions, this research provided a new explanation for the relationship between complexity and risk. Although this relationship has usually been conceptualized with simplistic cause-effect frameworks, this study revealed that they might have multi-level interactions affected by the mediating variables. Depending on the strategies implemented to manage complexity, uncertainty, and resilience, the complexity factors may be both the source and the consequence of the risk events. The conceptual relationships identified in this study can be used by other researchers to explore the risk-related factors in mega or other construction projects. Furthermore, based on the relationships identified between risk-related concepts, a risk assessment process was proposed to handle the complexity as a part of project risk management. While the existing risk assessment approaches in the literature are oriented towards treating the uncertainty, IRAP presents a systematic approach to link the static and dynamic complexity factors, too, with the risk events. Therefore, it can pave the way for a broader academic debate on addressing the complexity within the scope of risk management. Another important conceptual contribution of IRAP is integrating the phases of risk assessment. Although the identification, analysis, and response are executed as the consecutive steps of the risk assessment in traditional approaches, IRAP takes the effect of management strategies into account when identifying and analyzing the risk sources. Thus, it provides a network-based risk assessment approach through management strategies. Moreover, the ANP model provided more insights into the network of risk-related concepts. Local priorities assigned by the experts serve to interpret the conceptual links between risk, uncertainty, complexity, and management strategies over numerical values. Global priorities, on the other hand, present the combined impact of these links on different risk factors. Researchers can benefit from these findings to develop conceptual or analytical models for risk-related concepts.

The conceptual and analytical models in this study were developed according to the empirical findings from 11 mega construction projects. Validation studies were also based on empirical evidence. Correspondingly, this research also provides some empirical contributions. While there are many studies measuring complexity and risk separately, this study offers an approach to quantify their relationships. The proposed metric can contribute to the literature by explaining the relationship between complexity and risk numerically. The empirical results of the projects investigated in this study showed that a high level of complexity makes it more difficult to predict the impact of risks on the megaprojects. In addition to the quantitative findings, the interview data of the projects helped to make further deductions about the impact of the complexity on mega construction projects. Although complexity is usually considered a negative term in the literature, the empirical findings demonstrated that it could lead to opportunities when combined with the appropriate management strategies. These results can be elaborated, evaluated, and extended to other megaprojects. Furthermore, the demonstrative case study revealed that the risk level of a project dynamically changes throughout the project based on the variations in the source parameters. This finding may lead to the development of new risk monitoring approaches to capture non-linear and dynamic effects of the risk sources.

There are also some methodological contributions of this study regarding the mixed-methods research and ANP applications. Although mixed-methods research is not new to the project management domain, combining it with the empirical reality of the megaprojects and lived experience of the managers was the methodological originality of this research. The quantitative and qualitative results reported in the first phase of the research reflect the actual project events from the viewpoints of the managers. In this regard, the structured approach presented in the methodology can be replicated by future studies that aim to use mixed-methods design in the project actuality research. On the other hand, although the data collection process in ANP studies is usually troublesome, the interactive questionnaire tool used in this study contributed to both the knowledge elicitation process and the reliability of the results. It also facilitated the implementation of the expert panel. Therefore, the data collection tool developed in this study can also be beneficial for future ANP studies in terms of improving their validity.

The research findings are expected to contribute to the practitioners as well. One of the main motivations of this research was developing a holistic risk management approach that can be practically used by the managers of mega construction projects. In this respect, IRAP has the potential to draw a more comprehensive risk picture by capturing the risks originated from both complexity and uncertainty as well as the secondary risks concerning management strategies. Thus, it may help construction companies to improve their practices to comprehend the risks and forecast the project performance. Moreover, practitioners can benefit from other findings reported in this study. The most important complexity and risk factors in mega construction projects were compiled from the viewpoint of the managers. The weights of the ANP model also revealed the most significant risk sources in mega construction projects. The detailed analysis of the demonstrative case study provided further information about not only the risk sources that can potentially exist in mega construction projects but also the various management strategies that can be employed to deal with them. Consequently, the managers of mega construction projects can utilize the findings of this study to evaluate the factors to be included in their risk management plans.

7.3 Limitations of the Research

Despite the contributions of this research, there are also some limitations concerning the conceptual model, analytical model, and validation studies. The proposed conceptual model was based on the data obtained through interviews with 18 managers of 11 mega construction projects. Although the sample size is enough for qualitative data analysis used in this study, the validity of the quantitative findings should be tested with a larger sample. On the other hand, a limitation related to the qualitative analysis is that the research findings considerably depend on the interpretation and bias of the participants and researchers. Moreover, the research findings reflect the view of the managers responsible for mega construction projects undertaken by the Turkish construction companies. Studies that include different types of stakeholders from other countries can be conducted to make a comparative analysis or produce more generic findings. The limitations related to the analytical model stem from the assumptions explained in Section 5.1 to simplify the application of ANP. Risk scores were calculated over the weights of 17 complexity factors and two uncertainty categories only. Furthermore, the weights of the model were based on the subjective ratings of the five experts. However, the number of factors and the generic weights can be customized for different projects by following the methodology described for the ANP model. There are also limitations in validation studies due to the factors affecting the reliability of the risk assessment tests, as explained in Section 6.1.3. Moreover, similar to the 11 projects, findings from the demonstrative case study was based on retrospective analysis. Longitudinal case studies may better explain the sequence of risk events and their interactions with the complexity and uncertainty factors.

7.4 Recommendations for Future Research

This study also proposes avenues for future research. First of all, the findings reported for mega construction projects can be compared with other projects in terms of the interactions between risk-related concepts. Moreover, IRAP can be compared with different risk assessment approaches to evaluate the performance or applicability. Although IRAP was operationalized with an ANP model in this research, future studies can use other network-based quantitative methods, such as Bayesian networks, network theory, and system dynamics, to report their advantages and disadvantages over ANP. Furthermore, other potential benefits of IRAP, such as analyzing alternative risk scenarios for different management strategies and recording the lessons-learned for the forthcoming projects, can be tested with real applications. Future studies may also include developing decision support tools to facilitate the implementation of IRAP. Finally, it should be noted that this thesis is a part of a research and development project, entitled “PRICOVIS: Development of a Computer-Based Tool for Visualization of Complexity and Risk in Mega Construction Projects.” The research findings form a basis to develop a computer-based visualization tool, which will provide a better understanding and management of complexity and risk encountered in mega construction projects. In this respect, the visualization of the interactions between complexity and risk is a promising research topic.

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APPENDICES

A. The Interview Protocol

VOLUNTARY PARTICIPATION FORM
This research, supported within the scope of the TÜBİTAK 1001 program, is carried out by the faculty members Prof. Dr. İrem Dikmen Toker, Asst. Prof. Dr. Güzide Atasoy Özcan, and Prof. Dr. M. Talat Birgönül in the Civil Engineering Department of the Middle East Technical University. This form has been prepared to inform you about the scope of the research. **What is the purpose of this study?** The aim of the research is to understand the relationship between complexity and risk in mega construction projects. The research findings will provide a basis for developing a computer-based tool that can visualize the impact of these factors on projects. **How can you help us?** If you agree to participate in this study, you are expected to attend an interview that will take approximately two hours. The interview questions will ask your opinion on the complexity and risk factors in the megaproject you have managed. With your permission, the interview will be audio-recorded for qualitative data analysis purposes. **How do we use the information collected from you?** Your participation in this study shall be on a voluntary basis. During the interview, we will request no information that reveals your identity or the institution you work for. The collected data will only be used for scientific purposes, such as thesis studies and academic publications, without specifying any person or company name. The personal information in the voluntary participation form will not be matched in any way with the data you provide. **If you would like to have more information about the research:** Thank you for participating in this study. In order to get more information about the research, you can contact Prof. Dr. İrem Dikmen Toker (e-mail: idikmen@metu.edu.tr) or research assistant Hüseyin Erol (e-mail: herol@metu.edu.tr). ***I have read the information given above and agree to participate in this study voluntarily.*** (Please return the form after signing it.) **Name, Surname**   **Date**   **Signature**

PARTICIPANT INFORMATION

1. What is your education status?

○ Ph.D. ○ M.Sc. ○ B.Sc. ○ Other

2. What is your role in the project, and how long did you work in the project?

3. How many years of experience do you have?

years

4. What is your level of experience in large-scale/mega construction projects?

○ Very Low ○ Low ○ Medium ○ High ○ Very High

PROJECT INFORMATION

1. Project Name:

2. Project Location:

3. Project Type: (Highway, power plant, airport, etc.)

4. The Owner:

5. Project Sponsors: (Institutions funding the project)

6. The Contractor:

7. Joint Venture or Consortium Partners (If available):

8. Project Delivery System: (EPC Turnkey, Build-Operate-Transfer, etc.)

9. Contract Type: (FIDIC, Public Procurement Law, etc.)

10. Contract Payment Type: (Lump-sum, unit price, etc.)

11. Project Start Date:

12. Project Status: (In progress, completed, etc.)

13. Planned Project Duration or Completion Date:

14. Actual Project Duration or Completion Date:
(If the project is in progress, please state the expected project duration or completion date)

15. Contract Price: (In terms of the currency stated in the contract)

16. Planned Cost:

17. Actual Cost:
(If the project is in progress, please state the expected cost)

18. Peak Number of Workers:

19. Project Size: (In terms of length, area, volume, etc.)

INTERVIEW QUESTIONS (PRE-PROJECT RISK ASSESSMENT)					
1. Could you briefly explain the scope and unique characteristics of the project?					
Please explain					
2. Did you have a risk management plan at the beginning of the project?					
Please explain					
3. If you have a risk management plan, how and by whom it was prepared?					
Please explain					
4. Have you used or planned to use any risk management software/tools?					
Please explain					
5. Could you briefly explain the risks/uncertainties you anticipated at the beginning of the project?					
Please explain with examples					
6. Could you rate the expected impact of the risks on a 1-5 scale by considering the assumptions and decisions at the beginning of the project? (1: Very Low – 2: Low – 3: Medium – 4: High – 5: Very High)					
Country-Related Political and Economic Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Financial Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Contractual Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Owner-Related Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Procurement Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Project Management and Organization Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Construction-Related/Technological Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Design Risks	○ 1	○ 2	○ 3	○ 4	○ 5

INTERVIEW QUESTIONS (COMPLEXITY FACTORS)
The following questions are related to the complexity factors of the project. While answering these questions, please consider the given complexity definition: *"Complexity is the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system."* (Vidal and Marle, 2008)
C1: Size of the project
• Have you encountered difficulties arising from the physical size of the project?
Please explain with examples
Could you rate the size of the project? ○ 1-Very Small ○ 2-Small ○ 3-Medium ○ 4-Large ○ 5-Very Large
C2: Strategic importance of the project
• Does the project have a geopolitical significance or special meaning for the country? • If so, have you encountered difficulties arising from the importance of the project?
Please explain with examples
Could you rate the strategic importance of the project? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much
C3: Political or macroeconomic instability
• Have you encountered difficulties in the project arising from the political or economic conditions of the country?
Please explain with examples
Could you rate the political or macroeconomic instability? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much
C4: Variety of financial institutions or sponsors
• Have you encountered difficulties arising from the financial package of the project?
Please explain with examples
Could you rate the variety of financial institutions or sponsors? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much

C5: Interactions between the stakeholders

- Who were the main stakeholders in the project?
- How were the relationships between the stakeholders defined in the contract?
- Have you encountered difficulties in the project arising from the communication, information exchange, or coordination issues between the stakeholders?

Please explain with examples

Could you rate the interactions between the stakeholders?

○ 1- Too Few ○ 2-Few ○ 3-Moderate ○ 4-Many ○ 5-Too Many

C6: Inadequacy of the contract

- How well the clauses, obligations, and penalties were defined in the contract?
- Have you encountered difficulties arising from the contractual terms of the project?

Please explain with examples

Could you rate the inadequacy of the contract?

○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much

C7: Lack of technical experience

- Did the main stakeholders (owner, consultant, engineer, and contractor) have sufficient experience?
- Have you encountered difficulties in the project arising from the lack of technical experience?

Please explain with examples

Could you rate the lack of technical experience?

○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much

C8: Changes in the project scope

- Were there any significant changes in the scope throughout the project?
- If so, have you encountered difficulties arising from the changes in the project scope?

Please explain with examples

Could you rate the changes in the project scope?

○ 1- Too Few ○ 2-Few ○ 3-Moderate ○ 4-Many ○ 5-Too Many

C9: Unrealistic project targets
• Were the time, cost, and quality targets of the project defined realistically? • Have you encountered difficulties arising from unrealistic project targets?
Please explain with examples
Could you rate the unrealistic project targets? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much
C10: Unavailability of resources (labor, material, equipment)
• Was there a critical resource (labor, material, machinery/equipment, etc.) requirement in the project? • If so, have you encountered difficulties in the project arising from the coordination of the supply chain?
Please explain with examples
Could you rate the unavailability of resources (labor, material, equipment)? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much
C11: Interactions between the project disciplines
• Did the project require teams from different disciplines (civil, mechanical, electrical, etc.) to work together? • If so, have you encountered difficulties in the project arising from the lack of communication and coordination between these teams?
Please explain with examples
Could you rate the interactions between the project disciplines? ○ 1- Too Few ○ 2-Few ○ 3-Moderate ○ 4-Many ○ 5-Too Many
C12: Cultural diversity
• Were there any teams/companies with different cultural backgrounds (different nationalities, etc.) in the project? • If so, have you encountered difficulties in the project arising from cultural diversity?
Please explain with examples
Could you rate the cultural diversity? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much

C13: Multiple critical paths (parallel activities)
• Have you encountered difficulties in the project arising from the intensity of the schedule (interdependent activities that need to be performed simultaneously)?
Please explain with examples
Could you rate the multiple critical paths (parallel activities)? ○ 1- Too Few ○ 2-Few ○ 3-Moderate ○ 4-Many ○ 5-Too Many
C14: Staff and equipment mobility
• Have you encountered difficulties in the project arising from the staff and equipment mobility of the site?
Please explain with examples
Could you rate the staff and equipment mobility? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much
C15: Physical and logistic constraints
• Have you encountered difficulties in the project arising from the constraints (location, physical conditions, weather conditions, etc.) of the site?
Please explain with examples
Could you rate the physical and logistic constraints? ○ 1- Too Few ○ 2-Few ○ 3-Moderate ○ 4-Many ○ 5-Too Many
C16: Technological novelty of the project
• Did the project require a construction technology that has not been used before? • If so, have you encountered difficulties in the project arising from the newness of the construction technology?
Please explain with examples
Could you rate the technological novelty of the project? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much
C17: Originality of the project design
• Have you encountered difficulties in the project arising from the originality of the design?
Please explain with examples
Could you rate the originality of the project design? ○ 1- Too Little ○ 2-Little ○ 3-Average ○ 4-Much ○ 5-Too Much

INTERVIEW QUESTIONS (COMPARISON OF THE COMPLEXITY FACTORS)					
1. When you consider all the factors we have discussed so far, do you consider this project a complex project?					
Please explain					
2. What is the main reason you call it complex (or not)?					
Please explain					
3. Could you rate the contribution of each complexity factor to the overall project complexity? (1: Very Low – 2: Low – 3: Medium – 4: High – 5: Very High)					
C1: Size of the project	○ 1	○ 2	○ 3	○ 4	○ 5
C2: Strategic importance of the project	○ 1	○ 2	○ 3	○ 4	○ 5
C3: Political or macroeconomic instability	○ 1	○ 2	○ 3	○ 4	○ 5
C4: Variety of financial institutions or sponsors	○ 1	○ 2	○ 3	○ 4	○ 5
C5: Interactions between the stakeholders	○ 1	○ 2	○ 3	○ 4	○ 5
C6: Inadequacy of the contract	○ 1	○ 2	○ 3	○ 4	○ 5
C7: Lack of technical experience	○ 1	○ 2	○ 3	○ 4	○ 5
C8: Changes in the project scope	○ 1	○ 2	○ 3	○ 4	○ 5
C9: Unrealistic project targets	○ 1	○ 2	○ 3	○ 4	○ 5
C10: Unavailability of resources (labor, material, equipment)	○ 1	○ 2	○ 3	○ 4	○ 5
C11: Interactions between the project disciplines	○ 1	○ 2	○ 3	○ 4	○ 5
C12: Cultural diversity	○ 1	○ 2	○ 3	○ 4	○ 5
C13: Multiple critical paths (parallel activities)	○ 1	○ 2	○ 3	○ 4	○ 5
C14: Staff and equipment mobility	○ 1	○ 2	○ 3	○ 4	○ 5
C15: Physical and logistic constraints	○ 1	○ 2	○ 3	○ 4	○ 5
C16: Technological novelty of the project	○ 1	○ 2	○ 3	○ 4	○ 5
C17: Originality of the project design	○ 1	○ 2	○ 3	○ 4	○ 5

INTERVIEW QUESTIONS (POST-PROJECT RISK ASSESSMENT)					
1. Do you think unexpected events and risks occurred in the project because of the complexity factors?					
Please explain with examples					
2. Could you rate the actual impact of the risks on a 1-5 scale by considering the risk events that happened throughout the project? (1: Very Low – 2: Low – 3: Medium – 4: High – 5: Very High)					
Country-Related Political and Economic Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Financial Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Contractual Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Owner-Related Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Procurement Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Project Management and Organization Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Construction-Related/Technological Risks	○ 1	○ 2	○ 3	○ 4	○ 5
Design Risks	○ 1	○ 2	○ 3	○ 4	○ 5

INTERVIEW QUESTIONS (FOLLOW-UP QUESTIONS)
1. How do you evaluate the time, cost, and quality performance of the project?
Please explain with examples
2. What were the main reasons for the disputes and performance problems in the project, if they exist?
Please explain with examples
3. Could you exemplify the impact of the complexity and risk factors on the project performance?
Please explain with examples
4. What were the main lessons learned from this project?
Please explain with examples
5. What could have been done to reduce the complexity of the project or manage the complexity and risk better?
Please explain with examples

B. Consolidated Comparison Matrices

Table B.1. Matrix of the First Pairwise Comparison Set
(Risk Factors with respect to Overall Mega Construction Project Risk)

Factors	R1	R2	R3	R4	R5	R6	R7	R8
R1	**1.00**	2.00	3.00	2.00	4.00	4.00	5.00	5.00
R2	0.50	**1.00**	2.00	2.00	3.00	2.00	4.00	4.00
R3	0.33	0.50	**1.00**	0.50	3.00	2.00	3.00	3.00
R4	0.50	0.50	2.00	**1.00**	3.00	2.00	3.00	3.00
R5	0.25	0.33	0.33	0.33	**1.00**	0.33	2.00	2.00
R6	0.25	0.50	0.50	0.50	3.00	**1.00**	2.00	2.00
R7	0.20	0.25	0.33	0.33	0.50	0.50	**1.00**	0.50
R8	0.20	0.25	0.33	0.33	0.50	0.50	2.00	**1.00**
Consistency Ratio = 0.031580916								

Table B.2. First Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R1)

Factors	U1	U2
U1	**1.00**	7.00
U2	0.14	**1.00**
Consistency Ratio = 0.00		

Table B.3. Second Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R2)

Factors	U1	U2
U1	**1.00**	6.00
U2	0.17	**1.00**
Consistency Ratio = 0.00		

Table B.4. Third Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R3)

Factors	U1	U2
U1	**1.00**	0.25
U2	4.00	**1.00**
Consistency Ratio = 0.00		

Table B.5. Fourth Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R4)

Factors	U1	U2
U1	**1.00**	0.50
U2	2.00	**1.00**
Consistency Ratio = 0.00		

Table B.6. Fifth Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R5)

Factors	U1	U2
U1	**1.00**	1.00
U2	1.00	**1.00**
Consistency Ratio = 0.00		

Table B.7. Sixth Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R6)

Factors	U1	U2
U1	**1.00**	0.33
U2	3.00	**1.00**
Consistency Ratio = 0.00		

Table B.8. Seventh Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R7)

Factors	U1	U2
U1	**1.00**	0.25
U2	4.00	**1.00**
Consistency Ratio = 0.00		

Table B.9. Eighth Matrix of the Second Pairwise Comparison Set
(Uncertainty Categories with respect to R8)

Factors	U1	U2
U1	**1.00**	0.20
U2	5.00	**1.00**
Consistency Ratio = 0.00		

Table B.10. First Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R1)

Factors	T	O	E
T	**1.00**	0.20	0.11
O	5.00	**1.00**	0.25
E	9.00	4.00	**1.00**
Consistency Ratio = 0.068524339			

Table B.11. Second Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R2)

Factors	T	O	E
T	**1.00**	0.50	0.33
O	2.00	**1.00**	1.00
E	3.00	1.00	**1.00**
Consistency Ratio = 0.017591065			

Table B.12. Third Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R3)

Factors	T	O	E
T	**1.00**	0.33	0.33
O	3.00	**1.00**	2.00
E	3.00	0.50	**1.00**
Consistency Ratio = 0.051559208			

Table B.13. Fourth Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R4)

Factors	T	O	E
T	**1.00**	0.50	1.00
O	2.00	**1.00**	4.00
E	1.00	0.25	**1.00**
Consistency Ratio = 0.051559208			

Table B.14. Fifth Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R5)

Factors	T	O	E
T	**1.00**	0.50	1.00
O	2.00	**1.00**	1.00
E	1.00	1.00	**1.00**
Consistency Ratio = 0.051559208			

Table B.15. Sixth Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R6)

Factors	T	O	E
T	**1.00**	0.25	3.00
O	4.00	**1.00**	5.00
E	0.33	0.20	**1.00**
Consistency Ratio = 0.082467972			

Table B.16. Seventh Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R7)

Factors	T	O	E
T	**1.00**	5.00	9.00
O	0.20	**1.00**	4.00
E	0.11	0.25	**1.00**
Consistency Ratio = 0.068524339			

Table B.17. Eighth Matrix of the Third Pairwise Comparison Set
(Complexity Categories with respect to R8)

Factors	T	O	E
T	**1.00**	6.00	7.00
O	0.17	**1.00**	2.00
E	0.14	0.50	**1.00**
Consistency Ratio = 0.031121747			

Table B.18. Matrix of the Fourth Pairwise Comparison Set
(Technical Factors with respect to Technical Complexity)

Factors	C7	C8	C9	C13	C16	C17
C7	**1.00**	0.50	2.00	3.00	4.00	4.00
C8	2.00	**1.00**	3.00	3.00	5.00	4.00
C9	0.50	0.33	**1.00**	1.00	3.00	3.00
C13	0.33	0.33	1.00	**1.00**	2.00	2.00
C16	0.25	0.20	0.33	0.50	**1.00**	1.00
C17	0.25	0.25	0.33	0.50	1.00	**1.00**
Consistency Ratio = 0.016449221						

Table B.19. Matrix of the Fifth Pairwise Comparison Set
(Organizational Factors with respect to Organizational Complexity)

Factors	C1	C4	C6	C10	C11	C12	C14
C1	**1.00**	2.00	3.00	4.00	2.00	8.00	7.00
C4	0.50	**1.00**	2.00	3.00	0.50	7.00	6.00
C6	0.33	0.50	**1.00**	2.00	0.50	5.00	4.00
C10	0.25	0.33	0.50	**1.00**	0.33	5.00	4.00
C11	0.50	2.00	2.00	3.00	**1.00**	7.00	6.00
C12	0.13	0.14	0.20	0.20	0.14	**1.00**	0.33
C14	0.14	0.17	0.25	0.25	0.17	3.00	**1.00**
Consistency Ratio = 0.037161556							

Table B.20. Matrix of the Sixth Pairwise Comparison Set
(Environmental Factors with respect to Environmental Complexity)

Factors	C2	C3	C5	C15
C2	**1.00**	0.33	0.25	6.00
C3	3.00	**1.00**	2.00	8.00
C5	4.00	0.50	**1.00**	7.00
C15	0.17	0.13	0.14	**1.00**
Consistency Ratio = 0.082583218				

Table B.21. First Matrix of the Seventh Pairwise Comparison Set
(Management Strategies with respect to R1)

Factors	S1	S2
S1	**1.00**	8.00
S2	0.13	**1.00**
Consistency Ratio = 0.00		

Table B.22. Second Matrix of the Seventh Pairwise Comparison Set (Management Strategies with respect to R2)

Factors	S1	S2
S1	**1.00**	4.00
S2	0.25	**1.00**
Consistency Ratio = 0.00		

Table B.23. Third Matrix of the Seventh Pairwise Comparison Set (Management Strategies with respect to R3)

Factors	S1	S2
S1	**1.00**	0.50
S2	2.00	**1.00**
Consistency Ratio = 0.00		

Table B.24. Fourth Matrix of the Seventh Pairwise Comparison Set (Management Strategies with respect to R4)

Factors	S1	S2
S1	**1.00**	1.00
S2	1.00	**1.00**
Consistency Ratio = 0.00		

Table B.25. Fifth Matrix of the Seventh Pairwise Comparison Set (Management Strategies with respect to R5)

Factors	S1	S2
S1	**1.00**	2.00
S2	0.50	**1.00**
Consistency Ratio = 0.00		

Table B.26. Sixth Matrix of the Seventh Pairwise Comparison Set
(Management Strategies with respect to R6)

Factors	**S1**	**S2**
S1	**1.00**	0.20
S2	5.00	**1.00**
Consistency Ratio = 0.00		

Table B.27. Seventh Matrix of the Seventh Pairwise Comparison Set
(Management Strategies with respect to R7)

Factors	**S1**	**S2**
S1	**1.00**	0.33
S2	3.00	**1.00**
Consistency Ratio = 0.00		

Table B.28. Eighth Matrix of the Seventh Pairwise Comparison Set
(Management Strategies with respect to R8)

Factors	**S1**	**S2**
S1	**1.00**	0.50
S2	2.00	**1.00**
Consistency Ratio = 0.00		

Table B.29. First Matrix of the Eighth Pairwise Comparison Set
(Uncertainty Categories with respect to S1)

Factors	**U1**	**U2**
U1	**1.00**	0.50
U2	2.00	**1.00**
Consistency Ratio = 0.00		

Table B.30. Second Matrix of the Eighth Pairwise Comparison Set
(Uncertainty Categories with respect to S2)

Factors	U1	U2
U1	**1.00**	5.00
U2	0.20	**1.00**
Consistency Ratio = 0.00		

Table B.31. First Matrix of the Ninth Pairwise Comparison Set
(Complexity Categories with respect to S1)

Factors	T	O	E
T	**1.00**	0.50	0.33
O	2.00	**1.00**	0.50
E	3.00	2.00	**1.00**
Consistency Ratio = 0.008848762			

Table B.32. Second Matrix of the Ninth Pairwise Comparison Set
(Complexity Categories with respect to S2)

Factors	T	O	E
T	**1.00**	0.50	0.17
O	2.00	**1.00**	0.25
E	6.00	4.00	**1.00**
Consistency Ratio = 0.008848762			

Table B.33. Matrix of the Tenth Pairwise Comparison Set
(Complexity, Uncertainty, and Strategies Clusters with respect to Risk Cluster)

Clusters	Complexity	Uncertainty	Strategies
Complexity	**1.00**	1.00	4.00
Uncertainty	1.00	**1.00**	5.00
Strategies	0.25	0.20	**1.00**
Consistency Ratio = 0.005322223			

Table B.34. Matrix of the Eleventh Pairwise Comparison Set
(Complexity and Uncertainty Clusters with respect to Strategies Cluster)

Clusters	Complexity	Uncertainty
Complexity	**1.00**	1.00
Uncertainty	1.00	**1.00**
Consistency Ratio = 0.00		

C. The Unweighted Supermatrix

Table C.1. Priorities in the Unweighted Supermatrix

Components	C7	C8	C9	C13	C16	C17	C1	C4	C6	C10	C11	C12	C14	C2	C3	C5
C7	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C8	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C9	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C13	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C16	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C17	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C10	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C11	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C12	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000
C14	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000
C2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000
C3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000
C5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000
C15	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
T	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
E	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
U1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
U2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
S1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
S2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R7	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
OR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table C.1. (Cont'd) Priorities in the Unweighted Supermatrix

Components	C15	T	O	E	U1	U2	S1	S2	R1	R2	R3	R4	R5	R6	R7	R8	OR
C7	0.00000	0.25623	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C8	0.00000	0.36113	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C9	0.00000	0.14358	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C13	0.00000	0.11650	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C16	0.00000	0.05980	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C17	0.00000	0.06276	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C1	0.00000	0.00000	0.31686	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C4	0.00000	0.00000	0.18604	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C6	0.00000	0.00000	0.12057	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C10	0.00000	0.00000	0.08730	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C11	0.00000	0.00000	0.22707	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C12	0.00000	0.00000	0.02426	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C14	0.00000	0.00000	0.03791	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C2	0.00000	0.00000	0.00000	0.15117	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C3	0.00000	0.00000	0.00000	0.45931	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C5	0.00000	0.00000	0.00000	0.34842	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C15	1.00000	0.00000	0.00000	0.04111	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
T	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.16342	0.10615	0.06033	0.16920	0.13965	0.23183	0.25992	0.22554	0.74287	0.75825	0.00000
O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.29696	0.19288	0.23115	0.38737	0.52784	0.58417	0.41260	0.67381	0.19388	0.15125	0.00000
E	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.53961	0.70097	0.70852	0.44343	0.33252	0.18400	0.32748	0.10065	0.06325	0.09051	0.00000
U1	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.33333	0.83333	0.87500	0.85714	0.20000	0.33333	0.50000	0.25000	0.20000	0.16667	0.00000
U2	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.66667	0.16667	0.12500	0.14286	0.80000	0.66667	0.50000	0.75000	0.80000	0.83333	0.00000
S1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.88889	0.80000	0.33333	0.50000	0.66667	0.16667	0.25000	0.33333	0.00000
S2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.11111	0.20000	0.66667	0.50000	0.33333	0.83333	0.75000	0.66667	0.00000
R1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.28936
R2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.19387
R3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12319
R4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.15302
R5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.05997
R6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.09114
R7	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04081
R8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04865
OR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

D. The Weighted Supermatrix

Table D.1. Priorities in the Weighted Supermatrix

Components	C7	C8	C9	C13	C16	C17	C1	C4	C6	C10	C11	C12	C14	C2	C3	C5
C7	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C8	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C9	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C13	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C16	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C17	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C10	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C11	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C12	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000
C14	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000
C2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000
C3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000
C5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000
C15	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
T	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
E	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
U1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
U2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
S1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
S2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R7	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
OR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table D.1. (Cont'd) Priorities in the Weighted Supermatrix

Components	C15	T	O	E	U1	U2	S1	S2	R1	R2	R3	R4	R5	R6	R7	R8	OR
C7	0.00000	0.25623	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C8	0.00000	0.36113	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C9	0.00000	0.14358	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C13	0.00000	0.11650	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C16	0.00000	0.05980	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C17	0.00000	0.06276	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C1	0.00000	0.00000	0.31686	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C4	0.00000	0.00000	0.18604	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C6	0.00000	0.00000	0.12057	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C10	0.00000	0.00000	0.08730	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C11	0.00000	0.00000	0.22707	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C12	0.00000	0.00000	0.02426	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C14	0.00000	0.00000	0.03791	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C2	0.00000	0.00000	0.00000	0.15117	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C3	0.00000	0.00000	0.00000	0.45931	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C5	0.00000	0.00000	0.00000	0.34842	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C15	1.00000	0.00000	0.00000	0.04111	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
T	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.08171	0.05307	0.02612	0.07327	0.06047	0.10039	0.11255	0.09766	0.32169	0.32834	0.00000
O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.14848	0.09644	0.10009	0.16774	0.22857	0.25296	0.17867	0.29178	0.08396	0.06549	0.00000
E	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.26981	0.35049	0.30681	0.19202	0.14399	0.07968	0.14181	0.04359	0.02739	0.03919	0.00000
U1	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.16667	0.41667	0.40816	0.39983	0.09329	0.15549	0.23323	0.11662	0.09329	0.07774	0.00000
U2	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.33333	0.08333	0.05831	0.06664	0.37318	0.31098	0.23323	0.34985	0.37318	0.38872	0.00000
S1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.08933	0.08040	0.03350	0.05025	0.06700	0.01675	0.02512	0.03350	0.00000
S2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.01117	0.02010	0.06700	0.05025	0.03350	0.08375	0.07537	0.06700	0.00000
R1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.28936
R2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.19387
R3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12319
R4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.15302
R5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.05997
R6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.09114
R7	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04081
R8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04865
OR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

E. The Limit Supermatrix

Table E.1. Priorities in the Limit Supermatrix

Components	C7	C8	C9	C13	C16	C17	C1	C4	C6	C10	C11	C12	C14	C2	C3	C5
C7	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C8	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C9	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C13	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C16	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C17	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C10	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C11	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000
C12	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000
C14	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000
C2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000
C3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000
C5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000
C15	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
T	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
E	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
U1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
U2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
S1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
S2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R7	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
OR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table E.1. (Cont'd) Priorities in the Limit Supermatrix

Components	C15	T	O	E	U1	U2	S1	S2	R1	R2	R3	R4	R5	R6	R7	R8	OR
C7	0.00000	0.25623	0.00000	0.00000	0.00000	0.00000	0.02094	0.01360	0.00872	0.02073	0.01711	0.02746	0.03070	0.02651	0.08398	0.08574	0.02471
C8	0.00000	0.36113	0.00000	0.00000	0.00000	0.00000	0.02951	0.01917	0.01228	0.02922	0.02411	0.03870	0.04327	0.03737	0.11835	0.12085	0.03482
C9	0.00000	0.14358	0.00000	0.00000	0.00000	0.00000	0.01173	0.00762	0.00488	0.01162	0.00959	0.01539	0.01720	0.01486	0.04706	0.04805	0.01384
C13	0.00000	0.11650	0.00000	0.00000	0.00000	0.00000	0.00952	0.00618	0.00396	0.00943	0.00778	0.01248	0.01396	0.01206	0.03818	0.03899	0.01123
C16	0.00000	0.05980	0.00000	0.00000	0.00000	0.00000	0.00489	0.00317	0.00203	0.00484	0.00399	0.00641	0.00716	0.00619	0.01960	0.02001	0.00577
C17	0.00000	0.06276	0.00000	0.00000	0.00000	0.00000	0.00513	0.00333	0.00213	0.00508	0.00419	0.00673	0.00752	0.00649	0.02057	0.02100	0.00605
C1	0.00000	0.00000	0.31686	0.00000	0.00000	0.00000	0.04705	0.03056	0.03626	0.05755	0.07605	0.08405	0.06079	0.09580	0.03009	0.02438	0.05867
C4	0.00000	0.00000	0.18604	0.00000	0.00000	0.00000	0.02762	0.01794	0.02129	0.03379	0.04465	0.04935	0.03569	0.05625	0.01767	0.01431	0.03445
C6	0.00000	0.00000	0.12057	0.00000	0.00000	0.00000	0.01790	0.01163	0.01380	0.02190	0.02894	0.03198	0.02313	0.03645	0.01145	0.00928	0.02232
C10	0.00000	0.00000	0.08730	0.00000	0.00000	0.00000	0.01296	0.00842	0.00999	0.01586	0.02095	0.02316	0.01675	0.02640	0.00829	0.00672	0.01617
C11	0.00000	0.00000	0.22707	0.00000	0.00000	0.00000	0.03372	0.02190	0.02599	0.04124	0.05450	0.06024	0.04356	0.06865	0.02156	0.01747	0.04204
C12	0.00000	0.00000	0.02426	0.00000	0.00000	0.00000	0.00360	0.00234	0.00278	0.00441	0.00582	0.00643	0.00465	0.00733	0.00230	0.00187	0.00449
C14	0.00000	0.00000	0.03791	0.00000	0.00000	0.00000	0.00563	0.00366	0.00434	0.00688	0.00910	0.01006	0.00727	0.01146	0.00360	0.00292	0.00702
C2	0.00000	0.00000	0.00000	0.15117	0.00000	0.00000	0.04079	0.05298	0.05062	0.03337	0.02668	0.01676	0.02594	0.01171	0.00916	0.01084	0.03049
C3	0.00000	0.00000	0.00000	0.45931	0.00000	0.00000	0.12392	0.16098	0.15379	0.10139	0.08107	0.05091	0.07883	0.03558	0.02783	0.03294	0.09264
C5	0.00000	0.00000	0.00000	0.34842	0.00000	0.00000	0.09401	0.12212	0.11666	0.07692	0.06150	0.03862	0.05980	0.02699	0.02111	0.02499	0.07028
C15	1.00000	0.00000	0.00000	0.04111	0.00000	0.00000	0.01109	0.01441	0.01376	0.00907	0.00726	0.00456	0.00705	0.00318	0.00249	0.00295	0.00829
T	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
E	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
U1	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.16667	0.41667	0.42770	0.42161	0.12679	0.18480	0.25836	0.15430	0.12889	0.11124	0.28962
U2	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.33333	0.08333	0.08902	0.09511	0.38992	0.33192	0.25836	0.36241	0.38783	0.40547	0.22710
S1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
S2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R6	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R7	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
R8	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
OR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

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2019-Present	Hacettepe University Civil Engineering	Instructor
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PUBLICATIONS

1. Erol, H., Dikmen, I., & Birgonul, M. T. (2017). Measuring the impact of lean construction practices on project duration and variability: A simulation-based study on residential buildings. *Journal of Civil Engineering and Management*, *23*(2), 241–251. https://doi.org/10.3846/13923730.2015.1068846

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