

MULTI-CRITERIA DECISION-MAKING APPROACH FOR RISK MANAGEMENT IN MODULAR CONSTRUCTION PROJECTS

A Thesis

by

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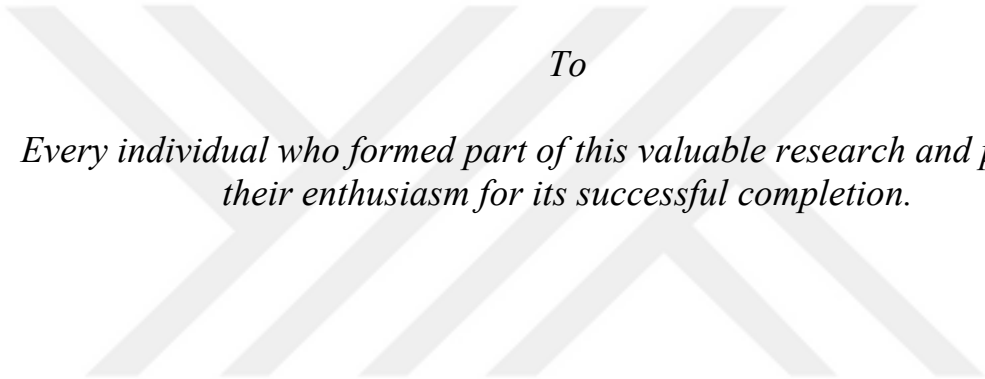
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To

*Every individual who formed part of this valuable research and provided
their enthusiasm for its successful completion.*

ABSTRACT

While there exists an ever-rising interest in modular construction projects, the current performance does not depict its full capabilities. This is mainly due to practicing ‘stick-built’ methods under a roof, implying carrying out conventional construction style in an offsite factory. That malpractice causes costs overruns, disruptions in timeline, and poor-quality end-products. Hence, early planning, guides, and qualified individuals should be integrated to eliminate those hindrances. While being minimal but not inexistent, the risks in a modular project can negatively impact overall performance if not tackled early on. As such, this study aims to utilize a multi-criteria decision-making approach for identifying the most efficient risk management approaches to tackle risks in modular construction projects. Hence, a systematic literature review, meta-analysis, semi-structured interviews with 5 experts, open-ended questionnaires with 5 experts who opted for sharing their input in this manner instead of interviews, and the 2- round Delphi method with 11 experts, were conducted. The data achieved underwent reliability, validity, and agreement tests comprising of calculations such as percentage standard deviation decrease, Cronbach’s alpha, and Kendall’s coefficient of concordance (Kendall’s W). This was followed by a meta-analysis with the content derived from the literature review. Hereafter, the Analytical Hierarchy Process (AHP) was opted to quantify the Delphi findings and solve the multi-criteria decision-making process. This has led to ranking the risk management approaches according to efficiency for each risk category considered in the scope of this study. These risk categories are Supply chain, Health & Safety of workers, Stakeholders, and Governmental support. The Delphi scores pertaining to efficiency performance of each risk management approach according to the relevant risk criteria was incorporated in the spreadsheet where AHP scores were

calculated. The AHP rankings are relevant to the mean efficiency score from Delphi round 2 and a uniformized weight value for risk criteria as a general approach. Practitioners can implement the spreadsheet with modified weight of the risk criteria according to their projects to derive precisely ranked risk management approaches. Furthermore, an interactive web-based application was launched using data achieved throughout the study to provide target audience with a user-friendly platform supporting early decision making in risk management. Once users select the risk category and criteria to tackle based on their projects, the application leads to guides on implementation of the risk management approaches alongside a to-do list. The application was validated by 3 industry experts for feasibility in integration to projects. The findings of this study will support early planning in a modular project by indicating to project managers or risk managers the most appropriate risk management approach to be implemented according to risk criteria of the project. The highly reliable Delphi and AHP findings provide practical insight for target audience in the modular construction industry such that a clearer initiation phase can be achieved. This would hence enable achievement of timelines, budget conditions and quality standards. The flexibility of the developed decision-making platform ensures that different projects can benefit from the latter based on their properties. Moreover, the research promotes continuous improvement in the modular construction industry by contributing to the quest of enhancing productivity through efficient risk management approaches usage.

GRAPHICAL ABSTRACT

RESEARCH PROBLEM



- "Stick-built" under a roof
- Lack of guide for modular risk management
- Malpractices leading to cost overruns and scheduling issues
- Lack of proven cases involving most efficient risk management approaches
- Applying conventional construction methodologies in offsite construction

RESEARCH AIM



- Identifying risk categories which demand urgent attention in the current modular construction industry
- Thoroughly portraying risk criteria for each risk category identified
- Indicating most efficient ranked risk management approaches category-wise
- Promoting efficient risk management with early-on decision making platform
- Developing an interactive web-based tool for identifying risk management approach according to specific risk criteria

METHODOLOGY



- Systematic literature review
- Semi- structured interviews and open-ended questionnaires
- Delphi method (2 rounds)
- Analytical Hierarchy Process (AHP)

DATA ANALYSIS



- Meta- analysis & setting foundation for Delphi stages
- Reliability and Validity tests for Delphi scores (Standard deviation, Cronbach's alpha, Kendall's W)
- Generating AHP scores for each risk management alternatives
- Ranking risk management approaches according to efficiency
- Interactive web-based application development for risk management guide

FINDINGS



- Current trends in risk management approaches of modular construction
- Risk categories, risk criteria and risk management approaches demanding urgent attention in the current industry
- Most efficient risk management approaches to tackle risk categories based on risk criteria
- User-friendly web-based application for early-on risk management guide
- Future work scopes to direct modular construction towards productivity and correct implementation



ÖZETÇE

Modüler inşaat projelerine sürekli artan bir ilgi olsa da, mevcut performans tam yeteneklerini göstermiyor. Bu, esas olarak, bir çatı altında 'birleştirme' yöntemlerinin uygulanmasından kaynaklanmaktadır ve bu da, tesis dışındaki bir fabrikada geleneksel inşaat tarzının gerçekleştirilmesi anlamına gelmektedir. Bu yanlış uygulama, maliyet artışlarına, zaman çizelgesinde aksamalara ve düşük kaliteli nihai ürünlere sebep olur. Bu nedenle, bu engelleri ortadan kaldırmak için erken planlama, rehberler ve kalifiye bireyler entegre edilmelidir. Modüler bir projedeki riskler minimal olmakla birlikte varolmasa da, erken ele alınmazsa genel performansı olumsuz etkileyebilir. Bu nedenle, bu çalışma modüler inşaat projelerinde riskleri ele almak için en verimli risk yönetimi tekniklerini belirlemek doğrultusunda çok kriterli bir karar verme yaklaşımı kullanmayı amaçlamaktadır. Bu amaçla sistematik bir literatür taraması, meta-analiz, 5 uzmanla yarı yapılandırılmış görüşmeler, görüşme yerine girdilerini bu şekilde paylaşmayı tercih eden 5 uzmanla açık uçlu anketler ve 11 uzmanla 2 türlü Delphi yöntemi kullanılmıştır. Elde edilen veriler, yüzde standart sapma azalması, Cronbach's alpha ve Kendall's uyum katsayısı (Kendall's W) gibi hesaplamalardan oluşan güvenilirlik, geçerlilik ve uyum testlerinden geçirildi. Bunu, literatür taramasından elde edilen içerikle bir meta-analiz izledi. Bundan sonra, Delphi bulgularını ölçmek ve çok kriterli karar verme sürecini çözmek için Analitik Hiyerarşi Süreci (AHP) tercih edildi. Bu durum, bu çalışma kapsamında ele alınan her bir risk kategorisi için risk yönetimi yaklaşımlarının verimliliğe göre sıralanmasını sağlamıştır. Bu risk kategorileri Tedarik zinciri, İşçi Sağlığı ve Güvenliği, Paydaşlar ve Devlet desteğidir. Her bir risk yönetimi yaklaşımının ilgili risk kriterlerine göre verimlilik performansına ilişkin Delphi puanları, AHP puanlarının hesaplandığı elektronik tabloya dahil edilmiştir. AHP sıralamaları, Delphi 2.

turdaki ortalama verimlilik puanı ve genel bir yaklaşıml olarak risk kriterleri için tek tipleştirilmiş ağırlık değeri ile ilgilidir. Uygulayıcılar, kesin olarak sıralanmış risk yönetimi yaklaşımları elde etmek için projelerine göre risk kriterlerinin değıştirilmiş ağırlığı ile elektronik tabloyu uygulayabilirler. Ayrıca, risk yönetiminde erken karar vermeyi destekleyen, hedef kitleye yönelik kullanıcı dostu bir platform sunmak için çalışma boyunca elde edilen veriler kullanılarak etkileşimli web tabanlı bir uygulama hayata geçirilmiştir. Kullanıcılar projelerine göre ele alınacak risk kategorisini ve kriterleri seçtikten sonra, uygulama bir yapılacaklar listesi ile birlikte risk yönetimi yaklaşımlarının uygulanmasına ilişkin kılavuzları sağlar. Uygulama, projelere entegrasyonda fizibilite için 3 sektör uzmanı tarafından doğrulandı. Bu çalışmanın bulguları, proje yöneticilerine veya risk yöneticilerine projenin risk kriterlerine göre uygulanacak en uygun risk yönetimi yaklaşımını göstererek modüler bir projede erken planlamayı destekleyecektir. Son derece güvenilir Delphi ve AHP bulguları, modüler inşaat sektöründeki hedef kitle için daha net bir başlangıç aşamasının elde edilebilmesi için pratik bilgiler sağlar. Bu, zaman çizelgelerine, bütçe koşullarına ve kalite standartlarına ulaşılmasını sağlayacaktır. Ayrıca araştırma, verimli risk yönetimi yaklaşımlarının kullanımı yoluyla verimliliği artırma arayışına katkıda bulunarak modüler inşaat sektöründe sürekli iyileştirmeyi desteklemektedir.

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CHAPTER I

INTRODUCTION

The construction industry has experienced a major upgrade with a growing interest in modular construction. In the past, conventional construction methods have reigned over for majority of the Architecture, Engineering and Construction (AEC) industry's timeline. Nowadays, traditional methods of construction do not meet the expectations of the society while causing an increase in construction period, loss of materials, low quality outputs, and rise in construction cost [1]. The emerging modular construction sector has thus attained ample interest due to the plethora of benefits compared to traditional construction. Given the exorbitant cost aspect of traditional construction alongside scheduling hassle, the modular construction sector has proven overcoming those hurdles, when correctly executed. Modular construction adopts a unique flow in the stages of construction. Raw materials in the inventory can be manipulated to elements, then combined to form components of a module. As for the whole modules, which a building consists of, these are crafted based on the convenience of transportation along with the vulnerability of the installation site. Off-site construction also comes with numerous environmental benefits [2]. For example, the manufacturing of modules in a factory occurs in a controlled environment which monitors energy use. Followed by the transportation of materials to factory and module to the site, less carbon emissions from the vehicles are witnessed, given the schedule timings for each step. Furthermore, noise and air pollution are a lot lower since manufacturing phases are not held at the project's actual site, and the demolition phase enables reusing and recycling of the components in every module due to the robust nature of the material used initially. Hence, modular construction contributes to sustainable construction.

1.1 Research problem

Since the labor force has not dealt with similar workflow concepts before, the main concern arises when the latter adopts the “stick-built” method under a roof [3]. Consequently, this leads to exceeding the project’s budget and schedule. The appropriate and most effective risk management approaches’ awareness is deemed as crucially prominent to maximize the actual benefits that the modular sector has in store. Given this, the current ever-growing interested bodies shifting to modular construction do not have established guide for efficient risk management. Providing a clear pathway for key decision makers to efficiently manage risks is needed and this can begin with developing guidelines for effective deployment of decision making by industry practitioners [4].

1.2 Research gap

Previous research has shed insights on the risks involved in modular construction and individually proposed how to tackle risk category being analyzed. Researchers have also performed case studies to showcase performance of proposed risk mitigation measures. Taking a deeper look into which risk categories demand immediate attention, it was identified that stakeholders such as government and developers have the highest impact for tackling the latter [5]. Accordingly, design risks not only hinder quality and pace of production but also decreases confidence of stakeholders to adopt off-site construction methods [6]. The key element to solve this lies in information flow. Effective communication and early involvement of stakeholders from supply chain stage are the success determinants for modular integrated construction projects [4]. Intensive

quantitative modeling of critical risk factors, critical success factors, barriers, and critical failure factors in modular construction was performed whereby comprehensive data was derived to aid target audience [7]-[9]. Whilst aiming to efficiently handle modular construction, a review on digital technologies with managerial integration sets the foundation for upcoming studies. Since the focus was laid on specific stages of a modular project, there is an obvious need for overall lifecycles consideration [10]. Although the mentioned studies have resulted in insightful data, limited work was seen in specific analysis of risk management approaches which are meticulously categorized according to project relevancy.

1.3 Research aim

To solve the research problem and fulfill the gaps, this study starts with analyzing literature published till date qualitatively and quantitatively, focusing on risk management of modular construction risks. The associated goals of this research are as follows:

- (1) Identifying the crucial risk categories which demand urgent attention in the current modular construction industry,
- (2) Thoroughly portraying risk criteria for each risk category identified and indicating most efficient ranked risk management approaches,
- (3) Promoting efficient risk management with early-on decision making for modular construction practitioners,
- (4) Developing an interactive web-based tool for convenient decision-making during risk management of modular projects.

In an effort to lead the modular construction sector to high productivity, the aims of this study act as a fundamental steppingstone to broaden existing knowledge level on risk

management approaches with a practical tool for the target audience. Furthermore, future work scopes are proposed to clarify potential research grounds for academicians and industry collaboration.

1.4 Research motivation

In the quest to direct the construction industry towards more efficient methods which do not negatively impact the surrounding areas, the concept partaking modular construction deem as the optimal choice. Furthermore, throughout the academic involvement, the risk management scopes have been seen to highly enhance a project's overall performance when conducted properly. This research has initially surveyed the loopholes which currently exist in the modular construction sector. With multiple opinions stating how the industry has a messed up initial plan and lack of clarity during decision making, the motivation of this study was further strengthened. Decision making is vital to derive a workable plan, for current situations and to establish grounds for future instances. To aid decision makers, which is a major part of the research motivation, the study paves the path for reliable early- on decision making in risk management. With the valuable output generation, the modular construction industry being a major target for improvement, can be further directed towards specificity while enabling its full capacity performance, hence achieving this study's motivation.

CHAPTER II

RESEARCH BACKGROUND

2.1 Risks in modular construction

With due consideration on different stages involved in modular construction and despite being an innovative method, risks are still involved [11]. Some aspects seen in modular construction projects are not working from height, reduced weather damages caused to material, not witnessing onsite mess due to many ongoing activities, no accidents due to various big vehicles navigating at the work site, among others. Nevertheless, existing risks require well established management approaches to achieve success with value-adding activities.

The stakeholder fragmentation and management complexity has ranked as first among the identified critical risk factors [4], [12]. This deduction indicates exactly which organizational level demands focus on risk management. Increased cost is identified among major factors affecting productivity of modular construction [13]. In identifying key risks that impact cost and schedule of modular construction, shortage of skilled labor and late design changes lead and establishing mitigation plans early on is necessary [14]-[16]. Upon carrying out a Failure Mode and Effects Analysis, half of the risk factors were workforce failures, and alarming cost overruns in the design phase [17]. Similarly, rework risks analyzed in the Chinese prefabrication sector add to the inefficiency of the industry [18]. With transformation to manufacturing concepts, employees are prone to hazards from tools, work area, and new technologies applied; hence, safety risks in prefabrication need attention [19]- [21]. Inexperienced contractors relying on traditional on-site construction style, and dealing with multiple types of components in prefabrication, root

for scheduling risks [22]-[24]. Investment risks have seen less attention but should be tackled for successful uptake of prefabrication [25]. It is denoted that early planning, collaboration, skilled labor choice, and motivation for investment by different stakeholders lead to efficient modular projects.

2.2 Risk management process in modular construction

Risk management is a fundamental pillar of all processes and projects. Upon identification of risks initially, the according management approach is matched pertaining to best performance. As an example, a generic risk management framework based on initial determination of risk factors impacting scheduling and cost serves this purpose. While involving a fuzzy analytical hierarchy process and with real time simulation, the risk assessment of a project is achieved [11]. Well-established supply chain configuration would ensure the scheduling and cost risks are better handled [26]. With a hybrid intelligent vehicle system, supply chain in prefabrication can be managed aiming to mitigate risks [27]. Scheduling risks collaboratively impact cost risks as an increase in time taken leads to cost overruns. With Building Information Modelling (BIM) and Radio Frequency Identification (RFID), a project can be monitored closely, and this risk management approach is viral in the current industry [28]. RFID tags on each component depict the overall trajectory and updates the team with real-time data via the BIM platforms [29]. BIM and Internet of Things (IoT) integration in modular integrated construction has allowed easy arrangement, smooth communication and early decision making during on-site assembly [30]. Machine learning and audio signals have been portrayed as eligible combinations for activity identification in modular construction, which tackles geometric risks [31]. Furthermore, a BIM based gateway was established

for stakeholders and project elements to have a common database facilitating integration and communication

The prefabrication industry adopting lean principles witnessed waste reduction and constraints removal [32]. Some lean tools are Last Planner System, Just in Time, Kaizen, Value Stream Mapping, while a lean method commonly implemented is Design for Manufacture and Assembly (DfMA). Health and safety are also among risks tackled by lean principles in modular assembly like the manufacturing industry [33]. As modular construction resembles production industries, tolerance analysis initially used in the latter would ease the risk management. Frameworks were successful in tackling process-related hurdles in modular high-rise buildings [34]. With an aim to tackle rework risks, using the Monte Carlo tolerance simulation in a prefabrication construction assembly showed success evidence [35]. Supply chain management including crane operations and planning, classify as critical success factors for full performance of modular projects [36], [37]

Many populated countries have opted for modular construction, being a cleaner production strategy, to meet demands of the citizens [38]. Life Cycle Assessments (LCA) and simulations carried out determine at the building operation phase which monitored aspects handle environmental risks [39]. While the modular sector is prone to lack of skilled workers, a great aid would be to have more qualitative framework [40]. An educational and innovative early on risk management approach was determined which not only inculcates the knowledge in participants but also shows how scheduling, quality, and cost risks are tackled. RFID/BIM/lean in prefabricated house production displays from the logistic phase to the assembly, how to integrate technologies and lean principles into a simulation project. The outputs of time optimized and meeting budgets were

noticeable to participants who are keen to implement such techniques in real world projects [41]. This indicates early collaboration of academic sector and industry deems as perfect fit for risk management.



CHAPTER III

RESEARCH METHODOLOGY

This study has opted for a mixed-methodological approach, being qualitative and quantitative, comprising of a systematic literature review, meta-analysis, semi-structured virtual interviews and questionnaires, the Delphi method, and the Analytical Hierarchy Process (AHP). Collating the findings from the given methods led to the development of an interactive web-based application which acts as a more convenient means for usage in the industry. Figure 1 depicts the overall flow of this study to achieve the stated goals. The methodology is further elaborated in sections 3.1-3.6.

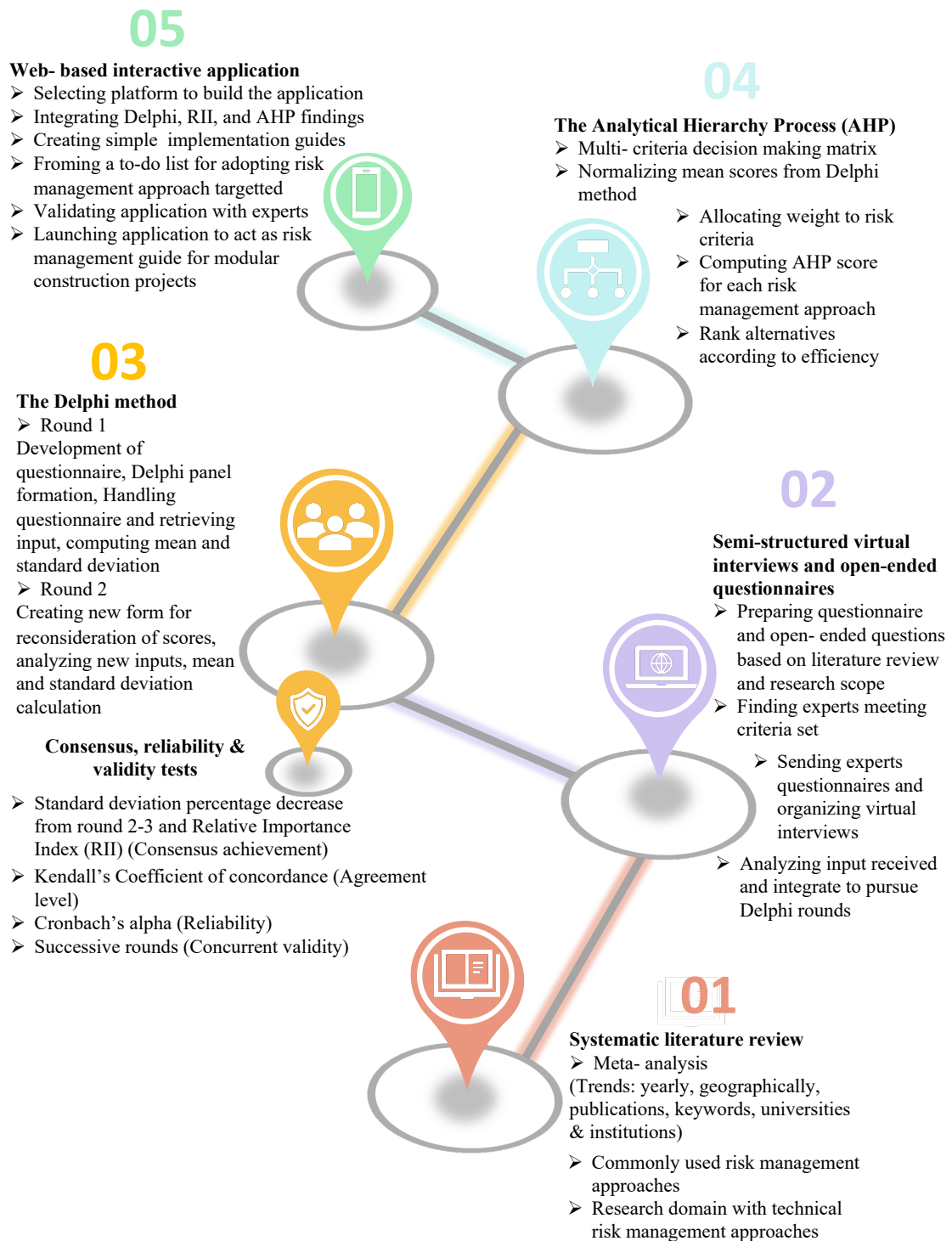


Figure 1: Research methodology process

3.1 Data flow in this study

Figure 2 depicts the data flow throughout major stages of this research. The initial phases consist of a Systematic literature review with the findings strengthened by perform semi-structured interviews and open-ended questionnaires. The overall deductions enable deriving crucial risk category demanding attention in the modular construction sector followed by risk criteria and management approaches. The Delphi method was pursued hereafter to enable experts rating the efficiency of the risk management approaches according to the according risk criteria. With the efficiency rating scores, the Analytical Hierarchy Process was opted to quantify the Delphi findings. The AHP solved the quest of ranking risk management approaches according to efficiency performance. Key decision makers in the construction sector can modify the weight of each risk criteria and achieve more specifically ranked risk management approach meeting demands of their project.

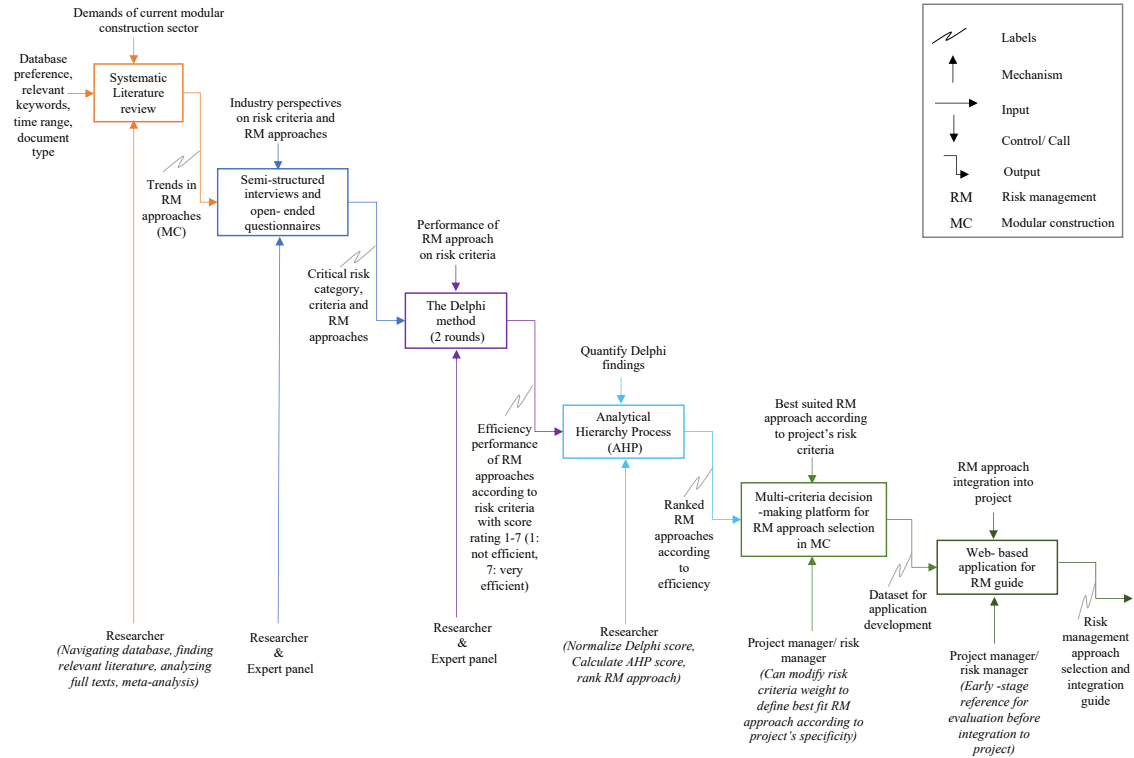


Figure 2: Data flow in this study

3.2 Systematic literature review and meta-analysis

This study has adopted a systematic literature review as part of the overall methodology to attain qualitative input followed by meta-analysis was to interpret the findings in a quantitative manner. Systematic literature reviews have the potential to clearly illustrate boundaries of scientific progress alongside current industrial practices in the research field [4]. Criteria such as keywords, document type, and language, were determined. Then, documents retrieved from Web of Science (WoS) core collections and Scopus were analyzed proceeding with title and abstract check. A total of 175 documents were finalized. Mendeley was chosen to store and handle the documents. The full texts were then read followed by meta- analysis. The latter is performed to shed light on

existing mixed empirical findings involving large amounts of literature [42]. Enriching illustrations were generated based on the literature found. These included yearly trends in publications, geographic spread of studies, publications' involvement, keywords frequently encountered, universities and institutions involvement, risk management approaches trends, and research domain focused on technical risk management approaches. In a meta-analysis, tables and figures derived require verbal explanation [43]. Hence, the research elaborates qualitatively in relation to each finding illustrated in the meta-analysis. Future work branches are provided in the scope of this study. Figure 3 summarizes the flow of the systematic review in this study.

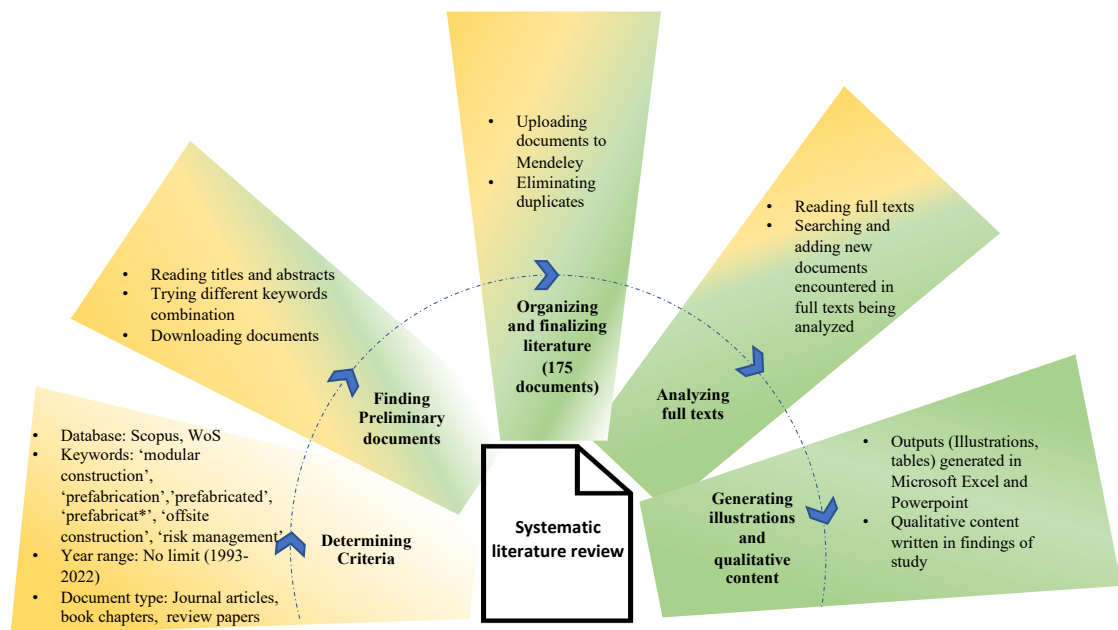


Figure 3: Systematic literature review process

3.2.1 Finding the preliminary literature

The database opted for in this study was Scopus and Web of science since they deem as highly enriched platforms with eased accessibility to meticulously identify literature desired. However, Scopus covered all findings retrieved from WoS, thus it was picked to find the literature. As such, the criteria and keywords implied were used to attain the desired studies:

(TITLE-ABS KEY (risk AND management)) AND (modular AND construction) AND (LIMIT-TO (DOCTYPE , "article") OR LIMIT-TO (DOCTYPE , "review") OR LIMIT-TO (DOCTYPE , "book")) AND (LIMIT-TO (LANGUAGE , "English")); 418 documents and after analysis of abstract 40 documents finalized, (TITLE-ABS-KEY (risk AND management)) AND (prefabrication) AND (LIMIT TO (DOCTYPE, “article”) OR LIMIT-TO (DOCTYPE , "review") OR LIMIT-TO (DOCTYPE, “book”)) AND (LIMIT-TO (LANGUAGE , "English")); 151 documents and after analysis of abstract 44 documents finalized, (TITLE-ABS-KEY (risk AND management)) AND (offsite) AND (LIMIT- TO (DOCTYPE , "article") OR LIMIT-TO (DOCTYPE, “review”) OR LIMIT-TO (DOCTYPE , "book")) AND (LIMIT-TO (LANGUAGE, “English”)); 281 documents and after analysis of abstract 28 documents finalized, (TITLE-ABS-KEY (modular AND construction)) AND (risk AND management) AND (LIMIT- TO (DOCTYPE, article") OR LIMIT-TO (DOCTYPE , "review") OR LIMIT-TO (DOCTYPE , "book")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "ENGINEERING")); 239 documents and after analysis of abstract 83 documents finalized, (TITLE-ABS-KEY (offsite)) AND (risk AND management) AND (LIMIT- TO (DOCTYPE , "article") OR LIMIT-TO (DOCTYPE , "review") OR LIMIT-TO (DOCTYPE, “book”)) AND (LIMIT-TO (SUBJAREA, “ENGINEERING”)) AND (LIMIT- TO (LANGUAGE , "English")), 116 documents and after analysis of abstract

39 documents finalized, (TITLE-ABS-KEY (prefabrication)) AND (risk AND management) AND (LIMIT- TO (DOCTYPE , "article") OR LIMIT-TO (DOCTYPE , "review") OR LIMIT- TO (DOCTYPE, “article”) OR LIMIT- TO (DOCTYPE , "review") OR LIMIT- TO (DOCTYPE , "book")) AND (LIMIT- TO (SUBJAREA, “ENGINEERING” AND (LIMIT- TO(LANGUAGE , "English")); 124 documents and after analysis of abstract 60 documents finalized. After narrowing down to the documents picked from title and abstract analysis, the pool of documents was narrowed down to 175 which were all eligible for this study’s scope.

3.2.2 Organizing and analyzing literature

175 documents were uploaded to Mendeley software. The latter is an easily navigable platform which not only stores documents but aids in the referencing process. This was followed by full texts analysis. Microsoft Excel was used for illustration generations, including clear graphs and tables. These outputs were followed by qualitative discussions and extended future work scopes.

3.3 Semi structured interviews and open-ended questionnaires

This stage had as aim to further ease the process of analyzing the topic and aid to reach specificity by integrating the industry experts’ inputs. Semi-structured virtual interviews and sending open-ended questionnaires to industry experts formed part of this step. The criteria abided by for selecting the experts consisted of having at least a bachelor’s degree in the Architecture, Engineering and Construction industry, and more than 5 years of experience in modular and more than 3 years in conventional construction. These have enabled setting a strong foundation to depend on for the upcoming stages. Details of the five experts involved in the interviews are illustrated in Table 1 below and

the five experts who opted for the open-ended questionnaires are illustrated in Table 2 below. The latter were found via LinkedIn and contacted with a short brief on the study's scopes and expectations from them. Examples of questions asked during the interviews and the questionnaire link can be found in *Appendix A*.

Table 1: Expert details for semi-structured interviews

No.	Education	Profession	Years of experience in modular construction	Years of experience in construction industry	Accreditation	Country	Interview duration (minutes)
E1	BSc Civil engineering, MBA	Process engineering & PMO manager	11	3	IASSC, Building construction quality management system	Brazil	96
E2	BSc Civil engineering, MBA	Managing Director	20	8	-	United Kingdom	19
E3	BSc Civil engineering, MBA	Chief Executive Officer (CEO)	22	10	-	United Arab Emirates	23
E4	BSc Civil engineering	Director	30	15	-	United Kingdom	44
E5	BSc Architecture	Continuous Improvement manager	27	10	LEED Accredited Professional	United Arab Emirates	60

Table 2: Expert details for open-ended questionnaire

No.	Education level	Job position	Years of experience	Years of experience	Licenses and certifications	Country
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			(Modular construction)	(Traditional construction)		
E1	PhD Engineering	CEO & institutional Director	5	10	-	United States of America
E2	BSc engineering	Site Manager	5	8	-	United Kingdom
E3	BSc engineering	Senior Electrical designer Modular construction	8	8	LEED Green Associate	United Arab Emirates
E4	BSc engineering	Modern Method Construction management consulting	15	8	-	United Kingdom
E5	BSc Mechanical engineering, PhD construction management	Head of Operations modular construction	14	10	Accréditation in Industrial Operations & Safety Régulations (EIOS), Certified Blockchain Expert (CBE), IOSH, Lean six sigma black belt (ICBB)	United Arab Emirates

3.4 The Delphi method

The Delphi method is a well-structured process which permits obtaining a reliable consensus from a well-qualified panel of experts where each member remains anonymous. The technique is very useful in situations that lack objective data or empirical evidence [44]. With precise monitoring at each round, consensus within the Delphi panel is the major quest. Additionally, results from the submitted questionnaires are analyzed by the researcher who then takes relevant measures to fix any loopholes and pave the way to reach consensus at every stage carried out [45]. By involving consecutive rounds after

receiving initial inputs, the findings are directed towards high precision and while being anonymous, bias is mitigated.

With all the content achieved from the systematic literature review, semi-structured interviews, and open-ended questionnaire, the Delphi method was pursued. The risk categories were finalized to "supply chain", "health & safety of workers", and "stakeholders and governmental support" after concluding with the experts and literature review that these categories demand urgent attention to redirect the modular sector on the path of efficiency. Accordingly, risk criteria were also identified and the relevant risk management approaches which fit the category were suggested. The following sections describes the detailed process of achieving a reliable Delphi method and Figure 4 shows the Delphi process in this study.

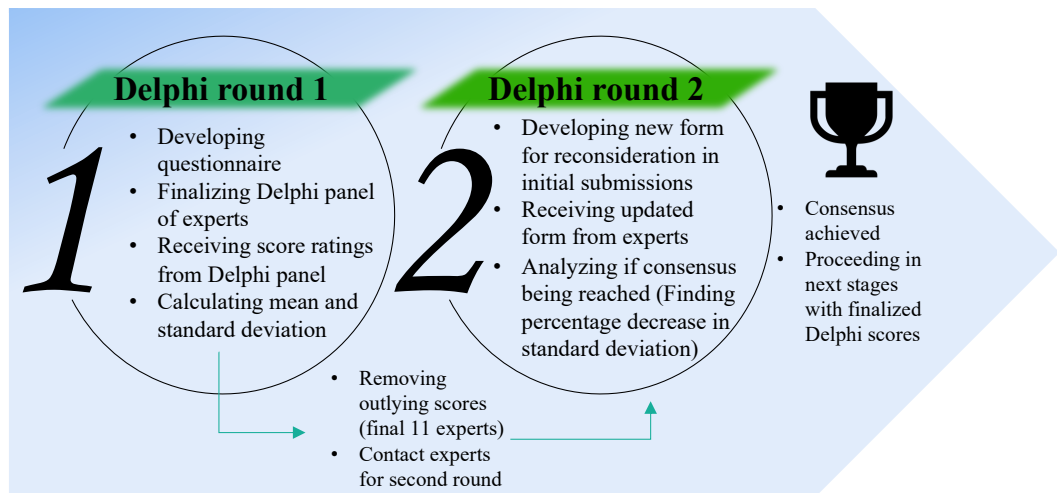


Figure 4: Delphi process in this study

3.4.1 Delphi round 1

3.4.1.1 Developing the questionnaire

In this stage, experts were responsible to assess efficiency levels of risk management approaches. The Delphi round 1 questionnaire was then created using all content achieved from the previous stages of this research. The latter was developed using JotForm which is highly interactive and data extraction can be done in an organized manner. Additionally, a 7-point Likert scale was opted for as information retrieval is maximized [45]. Similarly, inter-rater reliability is optimized from the usage of a 7-point scale [46], [48]. Given the above, the scope of rating efficiency of each risk management approach deemed more accurate with a 7 Likert scale that enabled experts having a wider precision in their choices. The scale was determined as follows; 1 referred to “not efficient” while 7 referred to “highly efficient”. The experts are instructed to rate efficiency of each risk management approach on each risk criteria for every risk category. To check the navigation process and structure, the questionnaire was sent to an academicians and an expert for feedback. Once the comments were taken into consideration, the questionnaire was ready to be sent to the Delphi panel. Snapshots of the questionnaire with the relevant link are attached in *Appendix B*.

3.4.1.2 Delphi panel of experts

In the quest to find eligible experts for the Delphi process, criteria were determined such as: having at least a bachelor’s degree in the AEC (engineering, architecture, construction management) industry, project management, and business management, having at least 3 years of experience in modular construction and at least 2 years in conventional construction, and being geographically distributed. LinkedIn was opted to connect with experts given the flexibility to filter through all aspects such as

experience, education, and current positions among others. An invitation message was sent with clear details about the goals and process of this study. The expectations from the experts were also pointed out to have clarity from the beginning. A total of 62 experts were found on LinkedIn who met the criteria to form part of the panel. In the Delphi method, given the specificity and quality of experts considered, 12 is regarded as the optimal amount to achieve reliable studies with 10 being the minimum. Invitations to 62 eligible experts were sent. However, 17 experts responded to the invite. The invitation process lasted from July 2021 to December 2021. The 17 experts were sent the questionnaire and relevant instructions. 12 experts responded with a filled questionnaire and one of the experts' inputs were very far off the inputs of other experts, hence the latter was not considered for upcoming stages. A total of 11 experts were then finalized as the Delphi panel responsible to determine the foundation of achieving this part of the study's methodology. Table 3 below shows the details of the Delphi panel of experts for both round 1 and 2:

Table 3: Delphi round 1 and 2 panel of expert's details

No .	Education level	Job position	Years of experience (Modular construction)	Years of experience (Conventional construction)	Years of experience (Risk management)	Licenses and certifications	Country
E1	Post-Graduation in Project Engineering and Management	Head of Operations	16	16	10	PMP, LSSBB, IOSH, SFC, CBE	United Arab Emirates
E2	BSc Architecture	Architect	5	2	2	-	United Arab Emirates
E3	MSc Engineering	Chief of quality and process	10	14	6	-	Chile

E4	BSc Engineering	Senior electrical designer	8	15	8	LEED GA	United Arab Emirates
E5	MSc Architecture	BIM lead	3	10	2	-	Australia
E6	BSc & MSc engineering	Innovation director offsite construction	4	8	3	-	Canada
E7	BSc Architecture	Modular studio director	9	20	8	-	United States of America
E8	BBA Business Management	CEO modular company	14	14	8	-	United States of America
E9	BSc Arts and design	President modular company	16	38	13	-	United States of America
E10	BSc Project management	Operations Construction Director	26	30	25	Black card CSCS (Construction Skills Certification Scheme)	United Kingdom
E11	BSc & MSc Civil engineering	Co-founder modular company	11	15	5	-	Turkey

Delphi round 1 lasted approximately 6 months (July 2021- January 2022), as the pandemic negatively impacted the work pace. The received inputs were thoroughly checked, mean, median values and standard deviation were calculated shown in Section 5.

3.4.2 Delphi round 2

In the second stage of the Delphi method, the aim is to achieve group consensus with a completely anonymous provision of insights regarding the Delphi panel's inputs.

A separate form was created individually for each of the 11 experts. The form consisted of the expert's initial score values, the overall mean value from the Delphi panel in first round and a section to make amendments if desired. The specific expert was then contacted via email and with details on the study's progress, the latter was instructed on how to handle this stage. In *Appendix C*, a sample of how the form was sent to the experts for second round is attached. This stage lasted from January 2022 to March 2022. Some experts have chosen to make amendments after checking the mean values. Hereafter, mean, median value, standard deviation values and relative importance index (RII) were calculated for this round. Equation 1 was used for calculating the RII [49]. W refers to score value given (i.e., from the previously determined 7-point Likert scale where 1 referred to "Not efficient" while 7 referred to "Highly efficient".), A is the maximum score value that can be given (i.e., 7) and N is the number of participants involved (i.e., 11 experts).

$$RII = \frac{\sum w}{(A*N)} \quad (1)$$

The RII and deductions are portrayed in the results section (section 5). This is to determine whether group consensus is achieved or not and rank the risk management approaches according to efficiency performance for each risk criteria. If the outcomes depict no agreement and doubts regarding efficiency performance for each risk management approach, another round should be conducted to inform the experts of the dispersity which exists.

3.5 Reliability and validity tests

Receiving initial questionnaire responses, the mean values, median and standard deviation were calculated for each risk management approaches rated by the experts. Additionally, the Cronbach's alpha and Kendall's coefficient of concordance (W) were calculated to determine reliability, validity, and agreement in the scores.

3.5.1 Standard deviation

The percentage decrease in standard deviation was calculated to deduce if experts' scores were being uniformized. This comparison was done by a simple summation of all standard deviations for that risk category and calculating the percentage difference from round 1 and 2 further discussed in Section 5.

3.5.2 Cronbach's alpha

Cronbach's alpha permits indicating whether the items are inter-related and consistent. The Cronbach's alpha value which deems acceptable to show the reliability of scores and internal inter-relatedness range from 0.7 to 0.95 [49], [51]. To measure reliability of the quantitative data received through the Delphi questionnaires, the Cronbach's alpha for both Delphi rounds was calculated and interpreted in the results sections (Section 5.4.2). Equation 2 was used where k is the number of items in a scale, σ_i^2 is the variance of i^{th} item and σ_t^2 is the variance of scale(total)scores [52]:

$$\alpha = \frac{k}{k-1} \left(1 - \frac{\sum_{i=1}^k \sigma_i^2}{\sigma_t^2} \right) \quad (2)$$

3.5.3 Kendall's coefficient of concordance, W

Further to this, Kendall's W values were calculated for each risk category in both Delphi rounds answered by experts. Computing this value indicates agreement level between experts [53]. Kendall's W is among the main consensus attainment techniques used in Delphi studies [54]. Equation 3 below was used to find Kendall's W for each risk category (i.e., supply chain, health and safety, stakeholders, and governmental support) and for both stages of the Delphi method. Before deriving the final coefficient value of W, R is computed using Equation 4 below [55], [56]. R indicates squared deviation of the ranking given to each risk categories. For example, the ranks given to each risk management approach for supply chain category is illustrated according to each expert's input. Then, the sum of ranks is calculated for each individual expert followed by the total sum of all ranks and mean value of the latter. Hereafter, a difference between the individual expert's sum of rank and mean rank for overall expert panel is found. This value is squared, and its sum for every risk management approach indicates R. This is used to achieve W, where m is number of experts and k is the subjects being rated, in this case the risk management approaches proposed [57]. Kendall's W for each risk category in round 2 and 3 of the Delphi method performed, are further discussed in Section 5.

$$W = \frac{12R}{m^2(k^3 - k)} \quad (3)$$

Where,

$$R = \sum_{i=1}^k (R_i - \bar{R})^2 \quad (4)$$

3.6 The Analytical Hierarchy Process (AHP)

The Analytical Hierarchy process was picked for achieving major scopes of this study. The AHP clearly separates a decision-making process into different stages making it specific and direct to the decision maker. With abundant multi-criteria decision making (MCDM) platforms in the field, comparison was made to select the best option with reference to an intensive study performed as shown below [58]:

- Weighted Sum Model (WSM) is most used in single dimensional problems and there is scope for hurdles when used in multi-dimensional MCDM problems,
- The ELECTRE method (Elimination and Choice Translating Reality; English translation from the French) provides an overall core of leading alternatives for a decision-making process and is unable to determine the most preferred one. Hence it fits when there are few criteria but many alternatives. In this study there is a balanced number of criteria and alternative, hence this method would not fit its purpose,
- TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) is also a variant of ELECTRE and was not picked for this study,
- As for the revised AHP, the latter is considered when some alternatives involved in the decision-making process are identical in terms of weight values. In this study, there is no such situation, hence the AHP technique is adopted with respect to all aspects and steps involved.

While integrating the Delphi method results with the AHP, the results can be quantified and proceed towards solving the multi-criteria decision aimed for [59]. This

study has sorted risk category and risk criteria for efficient risk management of modular construction. The multi-criteria approach helps to reach accuracy and covers the study's topic holistically. Additionally, using AHP method, matrices were formed which portray which is the best risk management approach for each risk category accordingly. These matrices are mounted by using the score values indicating effectiveness of risk management approaches for each criterion [58]. Figure 5 shows the AHP steps followed in this research.

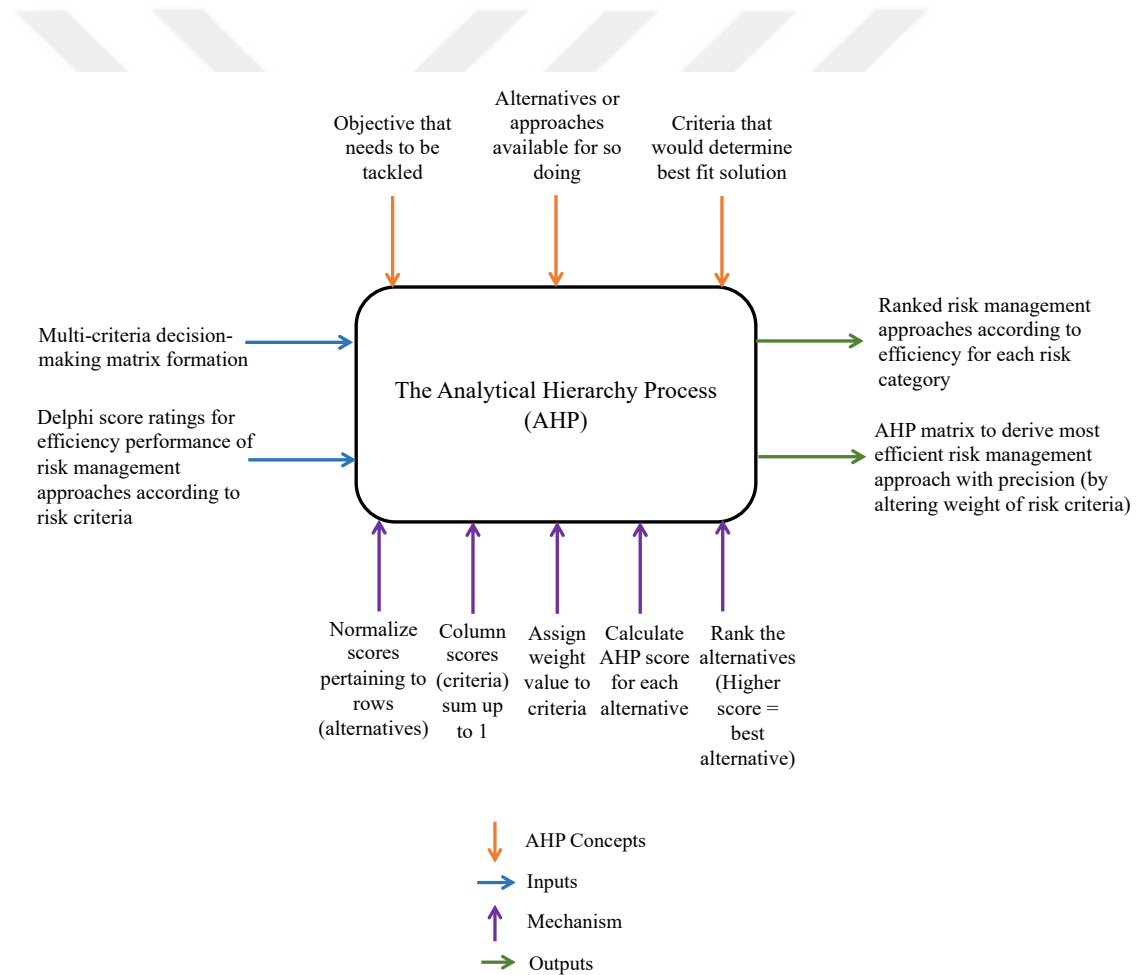


Figure 5: AHP steps in this study

The first step involved normalizing the mean score given to each risk management approach. The total of risk management normalized weight for specific criteria amounts to one. Hence, using equation 5 below, the AHP score for each risk management approach is calculated, where m is number of approaches, n is number of criteria, a_{ij} is normalized value of approaches on the criteria specified, and w_j is weight of each risk criteria [58]. Since there is no restriction on the weight criteria at this point, the value was added uniformly to get a general idea of best approaches meant for general modular projects. For example, if there are 5 criteria being dealt with, then the weight allocated is 0.2. Given different demands and prioritization of projects, the weight of project criteria can be modified to get more accurate risk management approaches ranked according to efficiency. This is followed by ranking the scores in descending order, where the largest value indicates the first and best risk management approach to tackle that criterion. The detailed calculations are shown in Section 5.

$$A_{AHP-score}^* = \sum_{j=1}^n a_{ij}w_j \text{ for } i= 1,2,3,\dots m. \quad (5)$$

CHAPTER IV

LITERATURE REVIEW FINDINGS

4.1 Meta-analysis

To analyze the systematic literature review's findings in a quantitative manner, a meta-analysis was carried out. This analysis allows for assessing relationship between variables and determining status of the intervention quantitatively [60]. The sections below show the findings from the systematic literature review in a meticulously categorized manner comprising of yearly publication trends, geographic involvement, publications' involvement, frequently encountered keywords, universities and institutions' involvement, risk management approaches identified and a research domain.

4.1.1 Yearly publication trend

The graph in Figure 6 shows yearly trend in publications relating to risk management in modular construction with the first published in 1993. No publication was seen from 1997 to 2006. This absence from researchers could be linked to the hardships being witnessed in the construction sector at that point such as economic downfalls, labor shortage, and governmental instability. An increase in new technologies and concepts have positively impacted the sector as from 2016 with the ultimate interest seen in 2021 corresponding to 55 documents. Seeing the trend in the past 5 years, potential increase in studies is highly likely until the end of 2022.



Figure 6: Yearly trend in literature

4.1.2 Geographic involvement

Figure 7 shows the geographical involvement of countries involved in modular construction studies with 2 or more documents. China is leading indicating eased availability of modern facilities which smoothens adoption and execution process of modular construction. For example, an IoT- based system supporting prefabrication in China was established [61]. To encourage the Chinese government in more adoption of prefabrication, its environmental benefits in contrast with conventional construction were depicted [62]. Adding to similar concepts, a cost-benefit analysis supported promotion of prefabrication in China [63]. For clearer insights, analyzing of policies to integrate prefabrication in the country and understanding perceptions of the stakeholders focused on costs incurred is crucially important [64], [65]. The latter is followed by Hong Kong, Australia, United Kingdom, United States, and Canada. Both developed and developing countries with significantly large populations resort to prefabrication and off-site construction techniques. The modular construction sector in Hong Kong benefits from identified critical success factors for embedding circular economy in the sector [66]. Additionally, steps towards deriving guides on productivity improvement for developing countries adopting offsite construction were taken [67]. Being the second most populated

country worldwide, India's construction sector showed interest in modular construction techniques, that currently lacks guidance and resources for holistic change [68]. Australia has potential interest in the sector with academicians analyzing the performance and current beliefs till date [69]-[71]. New Zealand academicians analyzed status of automation in the country with barriers to be overcome for promoting uptake of modular construction alongside analyzing supply chain performances [72], [73]. Despite Africa facing other discrepancies, 3 studies focused on South Africa showing interest in more efficient methods of construction.

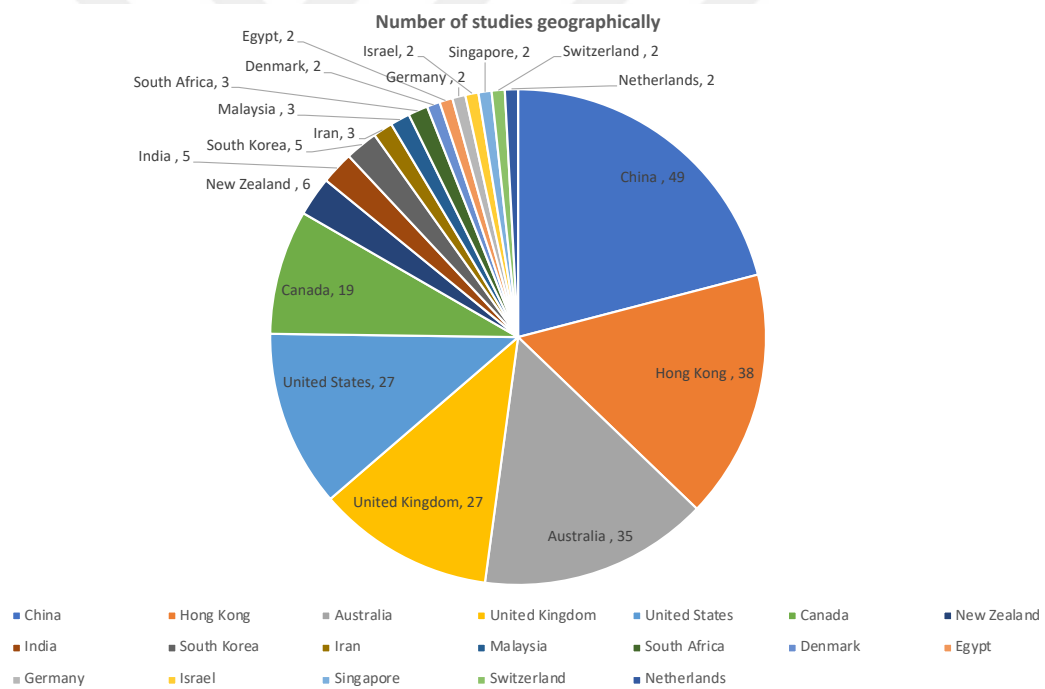


Figure 7: Geographical involvement

4.1.3 Publications' involvement

Figure 8 shows the involvement of journals, books, and reviews in the field of study with those publishing more than 2 documents included in the illustration. Journal of Cleaner Production, known as a high impact journal, takes the lead. This shows reliability in the content picked for the literature review of this study as most of the documents were published in this journal. Further, this high involvement rate, proves modular construction projects' potential in sustainable aspects. Automation in Construction ranks second showcasing the ever-rising integration of digital tools in modular construction due to similarity with manufacturing industry's concepts. The three journals ranking in the top five namely, Journal of Construction Engineering and Management, Engineering Construction and Architectural Management and International Journal of Construction Management, showing that good management is an important success factor in the field.

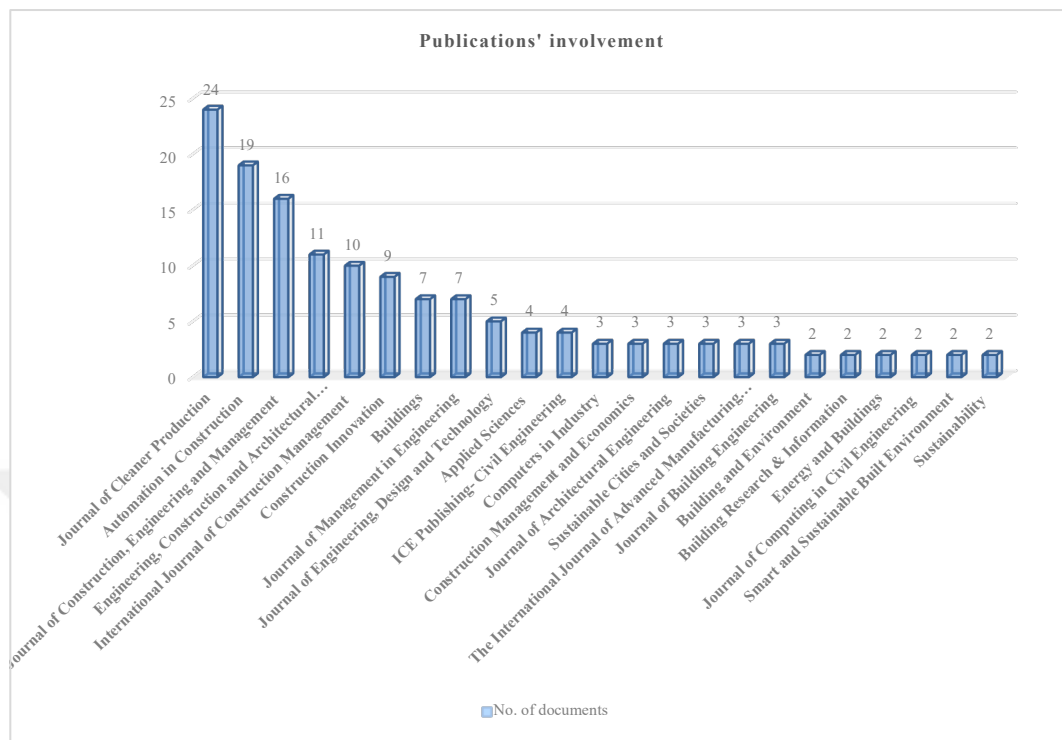


Figure 8: Publications' involvement

4.1.4 Frequently encountered keywords

Table 4 below illustrates the proportion occupied by keywords encountered more than 5 times. It was deduced that 'prefabrication' and 'offsite manufacturing/construction' were more implemented than 'modular construction'. This could be due to the literal and direct meaning these words hold. A greater percentage appearance of 'building information modelling' was seen than 'risk management'. Link between BIM and modular projects is abundant given success evidence seen. Appearance of keywords such as, 'life cycle analysis (LCA)', 'embodied carbon emission', 'carbon reduction', 'environmental performance', and 'construction waste', depicts academic involvement to widen the sustainability scopes. Frequent mentions of IoT and blockchain

proves strong risk management abilities. BIM and lean methods' collaboration have shown success in tackling design or safety risks and ensuring overall quality.

Table 4: Keywords' percentage appearance

Keywords (appearing > 5 times)	Percentage appearance
Prefabrication	11%
Offsite manufacturing/construction	11%
Modular Construction	9%
Building Information Modelling (BIM)	7%
Construction Management	6%
Project management	5%
Modular structures	5%
Case studies	5%
Risk Management	4%
Modular Integrated Construction	4%
Supply Chain Management	4%
Innovation	2%
Cost- benefit analysis	2%
Construction	2%
DfMA	2%
Decision making	2%
Sustainable development	2%
Decision Support systems	2%
Productivity	2%
Logistics	2%
Scheduling	2%
Construction methods	2%
Occupational safety	2%
Lean construction	2%
Stakeholders	1%
Construction costs	1%

4.1.5 Universities and institutions involvement

Universities and institutions that have been included in more than 2 studies were incorporated in Table 5 below. Hong Kong Polytechnic university is leading the list.

Corporate sectors have collaborated with the academic sector to achieve efficiency in projects. Some examples are; Chinese Academy of Agricultural Sciences, D.Y Patil Design Cell India, GOLDBECK Nord Niederlassung Germany, INAIL Rome, Institute of Machine Elements and Engineering Design Germany, Korea Institute of Construction Technology, National Building Research Institute Israel, Rolls- Royce PLC UK, Samsung C&T Corporation Korea, Tata Hitachi Construction Machinery Company LTD, K.Wah International Holdings Hong Kong, and National Institute of Technology Calicut. By sharing technical and academic concepts, key personnel are left with more elaborate references and can derive much better methodologies.

Table 5: Universities and institutions involvement

Serial No.	University or Institution name	No. of documents	Serial No.	University or Institution name	No. of documents
1	Hong Kong Polytechnic University	32	31	Beijing University	2
2	University of Hong Kong	15	32	Birmingham City University	2
3	Chongqing University	7	33	Central South University China	2
4	University of Alberta	7	34	Guangzhou University	2
5	University of Waterloo	6	35	Imperial College London	2
6	Concordia University	5	36	Incheon National University	2
7	Curtin University	5	37	Indian Institute of Technology	2
8	Deakin University	5	38	Jiangxi University of Finance & Economics	2
9	Loughborough University	5	39	Liverpool John Moore University	2
10	RMIT University	5	40	Ministry of Education, China	2
11	Shenzhen University	5	41	National University of Singapore	2
12	University of Melbourne	5	42	Northumbria University	2
13	Louisiana State University	4	43	Queensland University of Technology	2
14	Missouri University of Science and Technology	4	44	Seoul National University	2
15	Southwest University, China	4	45	Shandong Jianzhu University	2
16	Tsinghua University	4	46	Sichuan University	2

17	Bond University	3	47	Swinburne University of Technology	2
18	City University of Hong Kong	3	48	The University of Adelaide	2
19	Dalian University of Technology	3	49	Tianjin University	2
20	Massey University	3	50	University of Auckland	2
21	Monash University	3	51	University of California	2
22	Purdue University	3	52	University of Illinois	2
23	Southeast University, China	3	53	University of New South Wales	2
24	Tongji University	3	54	University of Nottingham China	2
25	University of Brighton	3	55	University of South Australia	2
26	University of Johannesburg	3	56	University of Toronto	2
27	University of Michigan	3	57	UNSW Canberra	2
28	University of Newcastle	3	58	Western Michigan University	2
29	University of Wolverhampton	3	59	Zhejiang University	2
30	Western Sydney University	3	60	University of New Brunswick	2

4.1.6 Risk management approaches identified

The process of risk management does not refer to finding one solution to eradicate risks, but instead to aid in identifying, early preparation, and monitoring of the risk implementation plan [6]. This study comes upfront in providing a set of meticulously arranged risk management approaches that have holistically covered risk categories and project criteria respectively. Table 6 below addresses the detailed risk management approaches trends with reference to the academicians proving workability and efficiency of the latter. Risk categories and project criteria were all found according to the referenced studies. Based on the authors' statement of which risk category and what type of project were considered, this study classified relevant risk management approaches that have shown success evidence in those studies. The simple and direct reachability of such approaches benefit key decision makers early on for efficient risk management. The most

applied and remarkable risk management approaches are further elaborated on in this section.

Table 6: Risk management approaches trend

Risk category	Risk target area	Risk management approaches	Project criteria for the according risk management approaches	References
Cost	Construction	DfMA	Prefabricated non-structural components of residential buildings	[84], [85]
		BIM, Big data, DfMA	Offsite construction	[77]
		SWOT analysis	Prefabrication in rural areas	[95]
		Generic risk management framework	Modular construction buildings	[11]
	Production management	Blockchain-enabled IoT-BIM platform	Off-site production sites	[79]
		Collaborative product development framework	Modular products	[97]
	Transportation	Optimization model	Modular healthcare facility, office, Commercial and educational buildings	[26],[100], [101]
		Construction site layout plans (CSLP) & genetic algorithm	Prefabricated buildings	[83]
	Seismic	Seismic Damage Resisting System (SDRS)	Modular multi-storey building in seismic regions	[116], [117]
	Production flexibility	Resource planning algorithms	Off-site manufacturers with variation in demand and resource availability	[123]
Time	Construction	Last Planner System (LPS)	Modular offshore wind construction	[90]
		DfMA	Prefabricated non-structural components of residential buildings	[84], [85]
		BIM, Big data, DfMA	Offsite construction	[77]
		Smart Work Packaging (SWP)	Prefabricated housing	[81], [113]

		BIM- Lean framework	Modular construction buildings	[89]
		RFID enabled BIM platform	Prefabricated housing	[29]
		Generic risk management framework	Modular construction buildings	[11]
	Production management	Just in Time	Offsite construction	[91]
		Collaborative product development framework	Modular products	[97]
		Simulated annealing algorithms	Modular construction	[106]
Stakeholder	Stakeholder interaction	Information exchange platform	Highly populated developing countries and fragmented construction industry	[5]
		Blockchain-enabled cyber-physical smart MiC platform	Modular integrated buildings	[80]
		SNA-based risk management approach	Prefabricated buildings	[98]
Design	Design	Detailed framework on Information feeding at design phase	Prefabricated schools in developed countries	[6]
		Construction Method Selection Model (CMSM)	Concrete prefabricated buildings	[103]
Supply chain	Supply chain	Communication, information sharing, early involvement	Modular integrated buildings	[85], [94]
		Blockchain-enabled IoT-BIM platform	Modular construction buildings	[79]
	Supply chain (Schedule risk)	Digital twin framework with BIM, IoT sensors and GIS	Modular project with full modules transportation	[30], [82]
		Two-stage stochastic programming	Modular construction	[105]
	Supply chain (Cost mitigation, quality guarantee)	Locally made material, Components based prefabrication	Low rise residential buildings	[118]
Governmental	Governmental inclusion	Add to emergency response plan (given speedy delivery), renovate with prefabrication methods, demonstrate success case for robust conclusions	Prefabricated housing	[70]
Safety	Safety	Safety Performance Cloud Model Evaluation	Prefabricated buildings	[19]

		Construction site layout plans (CSLP) & genetic algorithm	Prefabricated buildings	[83]
		Noise risk assessment & probability-based modelling	Modular construction	[106]
		Kaizen	Modular housing	[86], [87], [88]
		Digital twin framework with BIM and IoT	Prefabricated building Hoisting	[83]
		Bayesian Network probabilistic model	Offsite manufacturing	[124]
	Ergonomic	Automated post-3D visualization ErgoSystem	Modularized projects	[114], [115]
Geometric	Geometric	Probability impact risk model	Modularized projects	[35], [109], [110], [111], [112]
		Object detection with deep learning algorithms	Construction sites for modular projects	[107]
Operational	Managerial (Waste management)	Extended producer responsibility (EPR) analytical framework	Offshore prefabrication construction	[98], [99]
	Maintenance (structural)	BIM based data management system	Modular construction buildings	[125]
Environmental	Environmental	Two-period based carbon-economy equilibrium strategy	Modular products	[126]
	Environmental (Carbon emission)	A Data Quality Index based Monte Carlo Simulation	Prefabricated high rise buildings	[127]
Quality	Quality	BIM & DfMA	Offsite construction	[78]
		BIM based automated design and drafting of wood panels	Modular residential buildings	[128]
		Risk management system with deep learning modified teaching-learning-based optimization	Prefabricated buildings	[129]

4.1.6.1 Using BIM platforms

BIM was encountered on ample occasions in real time projects and academic fields of offsite construction [74]. BIM authoring software such as Revit, Bentley, and ArchiCAD are adopted by construction practitioners given flexibility of usage. Factors impacting the application of BIM country- wise should be investigated to facilitate integration in prefabrication [74]. At initial phases, BIM was chosen for portraying data

about the project and suppliers with integration to criteria set by project team. Hereafter, the Analytical Hierarchy Process determines the best supplier for the project [76]. Focusing on the efficient information flow and sharing of design alternatives, a framework combining BIM, DfMA (Design for Manufacture and Assembly), and Big Data perfectly served this purpose [77]. BIM and DfMA integration direct towards quality in offsite projects. Incorporating a framework which allowed all stakeholders including clients to see the model and attributes during mounting process, mitigated scheduling, quality, and cost risks [78].

The supply chain management performed using Blockchain-enabled IoT-BIM platforms reduced cost risks otherwise faced as storage costs [79]. In modular integrated construction, a blockchain-enabled cyber-physical smart MiC platform with digital twin incorporation has tackled stakeholders risks by improving information reliability and transparency [80]. To handle schedule risks, an RFID enabled BIM platform eases overall process with all organizational levels' collaboration, and real-time data capturing minute details of construction processes [81]. BIM platforms' potential in interoperability, efficient risk management, and early integration abilities leads to full performance of modular construction.

4.1.6.2 IoT, sensors and GIS

Within the scope of efficient logistics management for diminishing the risks, involving digital twin, IoT sensors and tracking of transportation via GIS, proves to be applaudable [82]. With GPS tags and BIM integrated IoT risk management approach, real time capture of progress at work promoting eased decision making and decreased cost overruns, is seen [30]. The BIM and IoT framework focused on safety at work monitors the hoisting process of a modular project and workers safety were guaranteed [83]. In

prefabricated projects, the use of the mentioned technologies ensures smooth transitions of components and eliminates non-value adding activities such as waiting time, inventory storage, weather impact and enables collaboration of the offsite and onsite teams.

4.1.6.3 Adopting Lean principles

Applying the lean method, Design for Manufacture and Assembly (DfMA), the cost risks of a prefabricated residential project were minimized and benefiting the scheduling risk management [84]. DfMA enablers such as early collaboration and simplistic design approaches to hinder prolonged project delivery are suggested [85]. Kaizen, being a lean tool, has significant abilities to tackle safety risks [86]-[88]. Value Stream Mapping (VSM) proves possibilities of achieving timelines in modular construction projects with integration to BIM platforms [89]. Schedule risks were successfully handled with the Last Planner System (LPS) applied in a modular mega- project [90]. Just in Time, a well performing lean tool, was adapted to form a component delivery framework which hindered scheduling risks otherwise encountered in the offsite factories [91]. Integrated design and construction project delivery have proven to tackle risks early on, however, practitioners in the off-site construction sector indicated the necessity of having experience for efficient integration [49].

4.1.6.4 Early involvement

Collaboration between research groups, designers, builders, clients and suppliers can direct a project towards significant success rates while mitigating risks [92]. The early involvement of supply chain stakeholders' forms part of the critical success determinants in modular construction. Vendor involvement would also enable handling execution risks [93]. With this implementation, project risks can be mitigated and boost efficiency at

work [85], [94]. SWOT (strengths, weaknesses, opportunities, and threats) analysis can be performed early on especially in rural areas where prefabrication will be implemented. This would enable determining success scopes to avoid cost risks and have better managerial scopes [95]. Procurement risks can be tackled upon adopting procurement models for identifying barriers of offsite sector and take novel measures accordingly [96].

A framework for collaborative product development and production of modular products was developed linking customer demands, achieving design alternatives, and evaluating these choices until achieving optimal choice. This efficient approach tackles quality, cost, and time risks with its ability to be incorporated in design and manufacturing stages [97]. The extended producer responsibility (EPR) analytical framework is useful in handling managerial risks. This framework allows early on ability for the offshore extended producer responsibility to be analyzed, agreed upon, and allocated. Benefits to sustainability aspects are expected too due to less waste generation [98], [99]. Early involvement of every stakeholder and involved body of a modular project promotes eradication of reworks.

4.1.6.5 Optimization models

Followed by early planning, optimization models are support factors which enable efficient initial decisions. For example, to minimize the transportation cost and storage of materials, an optimization model states accurate arrangement of storage areas, vehicles position and arrival times, optimal warehouse location and favorable assembly phases [26], [100], [101]. Being generic, the concept can be applied to multiple project types. Mathematical optimization models tackle the scheduling risks in modular construction factories [102]. Construction site layout plans (CSLP) supported by genetic algorithm has tackled the safety and cost risks related to transportation in prefabrication due to the

optimized hoisting usage suggestions given [83]. For concrete prefabricated buildings, a Construction Method Selection Model (CMSM) determines feasibility of a project and suggests alternatives accordingly [103].

Applying a programming model during logistics planning for waste management of offsite production tackles environmental risks as the latter gives optimal locations and vehicle arrangement diminishing impacts on environment [104]. Moreover, a two-stage stochastic programming approach for logistics planning can mitigate schedule risks of massive modular projects otherwise leaving environmental impacts [105]. Simulated annealing algorithms indicate best case scenarios and give construction managers eased alternatives to handle cost and schedule risks [106]. Object detection from deep learning algorithms significantly improves monitoring in the factories to diminish human errors [107]. This ranks highly as a risk management approach while tackling time and quality risks. Focusing on worker's wellbeing, an optimization framework has been derived to determine best fit design options of modular construction projects [108].

4.1.6.6 Probabilistic methods and simulation

Geometric risk involves occasions when there is lack of coordination and adjustment or reworks are needed. By performing Monte Carlo tolerance simulation, the tolerance behavior in prefabrication can be predicted. Thus, concerned individuals analyze alternatives and handle the risk of reworks [35], [109]-[112]. A generic risk management framework identifies risk factors ranked according to highest impact on cost and schedule risks, indicating to the construction team urgent action required [11].

Prefabricated housing sees fragmentation that initiates severe scheduling risks. To tackle this, Smart Work Packaging (SWP) including social network analysis, system dynamics, discrete event simulation, and scenario analysis service, deem as enriched risk

management approach [81], [113]. The team benefit from early identification of optimal processes and multiple scenarios to meet scheduling demands. Ergonomic risks faced during construction and assembling of modular construction projects, can be handled with simulations too. Automated post-3D visualization ErgoSystem provides best lifting and placing positions for workers which also minimizes cost overruns due to human error, followed by delays [114], [115]

4.1.6.7 Seismic Damage Resisting System (SDRS)

In seismic regions, modular projects are faced with this extra risk. However, with the help of an SDRS, the cost impacts of this risk can be tackled. The brief details of such a system would include how the frames and damper systems are designed and installed. Hence, with an early adoption of such systems, seismic risks can be dealt with cost-effectively [116]. Advancement in connections and method applied for steel-based modular projects in seismic zones are analyzed and classified so that management approaches can be established easily by key decision makers [117].

4.1.6.8 Locally made materials & component-based prefabrication

While making use of overseas materials for module production, scheduling, cost, and quality risks are highly likely to be encountered. Using locally made materials, offsite production is expected to proceed with quality until the assembly phase. Similarly, depending on location of the project, component-based prefabrication is recommended due to eased of transportation [118]. In developing countries, restrictions of road-transported modular components' size are set to 3.5- 4 meters wide and 15- 16.5 meters long [119]. Given the mentioned constraints, the risk management approach stated promotes value-adding activities in a project while eliminating waste production.

4.1.7 Research domain about technical risk management approaches

Current technological innovations have radically boosted the scope for modularization [120]. Figure 9 demonstrates a research domain regarding trends and connection between the technical risk management approaches identified in this study. The link is shown between the relevant authors with similar research aims and risk categories targeted while also indicating continuation studies. Furthermore, the risk management approach implemented were specified into specific phases (i.e., design or construction). In this research domain, researchers can directly spot where attention was mostly laid in terms of technical risk management approaches. A wide array of study was involved in the project's early phases or early integration of risk management platforms such as optimization models and simulations. Fifteen studies performed probabilistic risk management approaches or simulations to determine optimal choices for the projects considered. Even though modular construction has better natural calamities resilience, meticulous consideration is needed during designing. Two studies were involved in this subject matter. IoT, Sensors, and GIS have incredible potential with integration to BIM platforms shown by three studies.

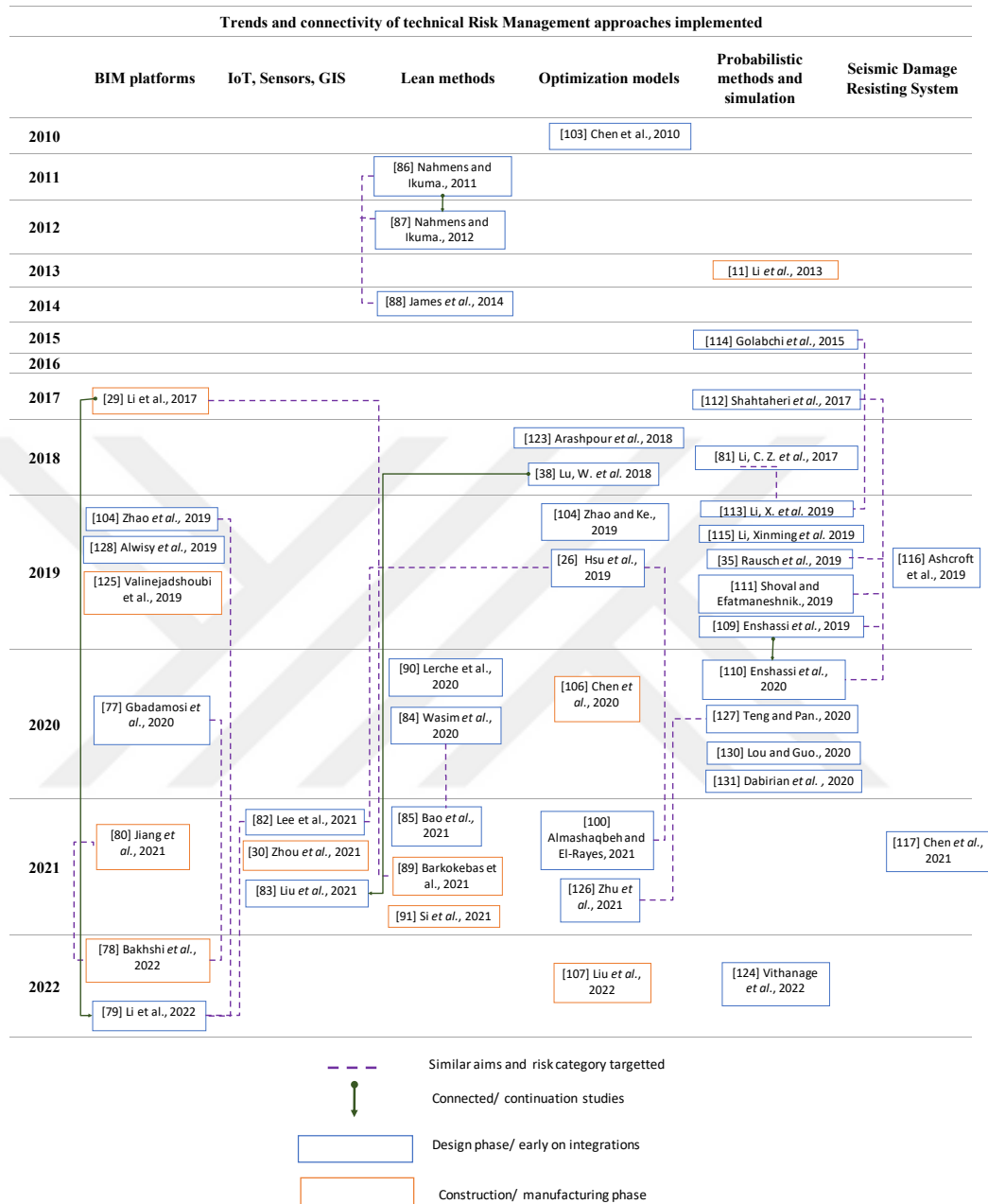


Figure 9: Research domain regarding trends in technical risk management approaches

CHAPTER V

RESULTS

5.1 Multi-criteria decision making (MCDM)

In a MCDM process, there are certain criteria which are often labelled as $C_1, C_2, \dots$ and alternatives which are provided in terms of $A_1, A_2, \dots$ that directs the decision making process towards specificity. As such, the criterion receive weight values (i.e., $w_1, w_2, \dots$) to depict their impact on the decision being made. These weights are normalized, so that their sum is equal to one [58]. MCDM problems can be expressed in a matrix, with rows and columns indicate alternatives and criteria, respectively [121]. Example of the matrix used in this study can be found in Table 7 below where X represent score rating given from Delphi panel experts for risk management approaches (alternatives, A) according to the risk criteria (C). For example, X_{21} indicates score given for effectiveness of alternative A_2 on criteria C_1 .

Table 7: MCDM matrix used in this study

		RISK CRITERIA				
		C1	C2	C3	C4	C5
		Criteria weight				
		w1	w2	w3	w4	w5
RISK MANAGEMENT APPROACHES/ ALTERNATIVES	A1	X_{11}	X_{12}	X_{13}	...	...
	A2	X_{21}	X_{22}	X_{23}	...	...
	A3	X_{31}	...	...	...	...
	A4	...	...	...	...	...
	A5	...	...	...	...	...
	A6	...	...	...	...	...
	A7	...	...	...	...	...

5.2 Semi- structured interviews and open-ended questionnaires

The replies from the experts for the questions entertained have provided a rich foundation to be analyzed and implemented for the upcoming stages. As shown in Table 8 below, the risk category, criteria and management approaches were identified. These were narrowed down upon meticulous comparison and consideration from the expert's experience- based insights.

Table 8: Identified risk category, risk criteria and risk management approaches

Risk Category	Risk Criteria	Risk Management Approach
Supply chain	Lacking communication with local supply chain regarding highway rules and module size allowed	Using the Last Planner System
		Adopting Kanban technique
		Using Just in Time concept
		Using BIM platforms
	Witnessing clashes in the designed elements for modules	Using the Last Planner System
		Adopting Kanban technique
		Using Just in Time concept
		Using BIM platforms
		Opting for locally made materials and simplified designs
		Including tradesmen with experience instead of only designers
		Using Radio Frequency Identification tags
		Adopting Value Stream Mapping until project is delivered to client
	Having no early involvement of client and contractors in the project	Using the Last Planner System
		Using BIM platforms
		Adopting Value Stream Mapping until project is delivered to client
	Design team lacking experience and making use of unestablished design standards	Motivating Government for support and requesting grants
		Involving engineers and architects to tailor design standards based on experience

Health & Safety	Dealing with multiple suppliers	Ensuring team members are qualified at or above a set academic/experience benchmark
		Using the Last Planner System
		Adopting Kanban technique
		Using Just in Time concept
		Using BIM platforms
		Using Radio Frequency Identification tags
		Adopting Value Stream Mapping until project is delivered to client
	Workers having ergonomic injuries	Making it compulsory for everyone on the project to have Health & Safety certification before starting
		Adopting Kaizen concepts in all tasks
		Using the Last Planner System
		Having a team supervisor for each task station
		Providing an additional worker in specific task usually performed by one individual
		Using robotics for lifting and placing elements
		Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements
	Team members getting electrocuted during module manufacturing	Making it compulsory for everyone on the project to have Health & Safety certification before starting
		Adopting Kaizen concepts in all tasks
		Using the Last Planner System
		Having a team supervisor for each task station
		Providing an additional worker in specific task usually performed by one individual
	Individuals getting hit by machinery during module production	Making it compulsory for everyone on the project to have Health & Safety certification before starting
		Adopting Kaizen concepts in all tasks
		Using the Last Planner System

		Having a team supervisor for each task station
Stakeholders	Having irregular data flow throughout the project	Using BIM platforms
		Using the Last Planner System
		Adopting decision making platforms at early stages
	Witnessing stick- built method under a roof	Using BIM platforms
		Using the Last Planner System
		Ensuring that the Engineer/Architect are well-versed in modular construction
	Experiencing poor communication between involved parties in the project	Using BIM platforms
		Using the Last Planner System
		Adopting decision making platforms at early stages
Governmental Support	Lacking interest from Government to opt for modular construction projects rather than conventional construction	Providing clear proof of previous cases and explaining concerned bodies
		Proposing vertical integration-selling buildings as products (e.g., cars)
		Providing more qualitative and educational content including basic details
	Unavailability of established rules country-wise focused on modular construction projects	Requesting for financial aid to enable qualified Engineers/ Architects to set building codes and standards specifically for modular projects
		Providing clear proof of previous cases and explaining concerned bodies
		Analyzing frameworks adopted by other countries and amend to suit current geographical demands

5.3 The Delphi method

The Delphi method in this study was comprised of 2 rounds whereby Delphi panel of experts rated efficiency performance of risk management approaches on relevant risk criteria for four major risk categories. The sub-sections depict the findings in detail.

5.3.1 Delphi round 1

Table 9 below shows mean, median, and standard deviation values calculated with the Delphi panel of experts during round 1. The rating scale applied was 1-7 where 1 referred to “Not efficient” while 7 referred to “Highly efficient”. Microsoft Excel was used to compute the following and the spreadsheet can be reached from *Appendix D*.

Table 9 : Mean, median and standard deviation for Delphi round 1

Risk Category	Risk Criteria	Risk Management Approach	Round 1 Mean value	Round 1 median	Round 1 standard deviation
Supply chain	Lacking communication with local supply chain regarding highway rules and module size allowed	Using the Last Planner System	4.75	5.00	1.45
		Adopting Kanban technique	4.42	4.00	1.35
		Using Just in Time concept	4.08	4.00	1.75
		Using BIM platforms	5.50	6.00	1.04
	Witnessing clashes in the designed elements for modules	Using the Last Planner System	5.08	5.00	1.01
		Adopting Kanban technique	4.25	4.00	1.13
		Using Just in Time concept	3.67	4.00	1.58
		Using BIM platforms	6.42	6.00	0.67
		Opting for locally made materials and simplified designs	4.75	5.00	1.58

		Including tradesmen with experience instead of only designers	5.58	6.00	1.08
		Using Radio Frequency Identification tags	4.92	5.00	1.27
		Adopting Value Stream Mapping until project is delivered to client	5.58	6.00	0.87
	Having no early involvement of client and contractors in the project	Using the Last Planner System	3.00	3.00	1.78
		Using BIM platforms	4.33	5.00	2.34
		Adopting Value Stream Mapping until project is delivered to client	3.83	4.00	1.92
	Design team lacking experience and making use of unestablished design standards	Motivating Government for support and requesting grants	4.08	4.00	1.35
		Involving engineers and architects to tailor design standards based on experience	5.58	6.00	1.04
		Ensuring team members are qualified at or above a set academic/experience benchmark	6.17	7.00	1.01
	Dealing with multiple suppliers	Using the Last Planner System	4.92	5.00	1.04
		Adopting Kanban technique	4.92	5.00	1.30
		Using Just in Time concept	4.08	4.00	1.83
		Using BIM platforms	5.58	6.00	1.27
		Using Radio Frequency Identification tags	4.83	5.00	1.17
		Adopting Value Stream Mapping until project is delivered to client	5.25	5.00	1.19
Health & Safety	Workers having ergonomic injuries	Making it compulsory for everyone on the project to have Health & Safety certification before starting	5.67	6.00	1.80
		Adopting Kaizen concepts in all tasks	4.33	5.00	1.21
		Using the Last Planner System	4.00	4.00	1.08
		Having a team supervisor for each task station	5.00	6.00	1.38

		Providing an additional worker in specific task usually performed by one individual	4.42	5.00	1.27
		Using robotics for lifting and placing elements	6.25	6.00	0.98
		Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements	5.50	6.00	1.03
	Team members getting electrocuted during module manufacturing	Making it compulsory for everyone on the project to have Health & Safety certification before starting	6.33	7.00	1.03
		Adopting Kaizen concepts in all tasks	4.25	4.00	1.21
		Using the Last Planner System	3.67	4.00	1.45
		Having a team supervisor for each task station	5.00	5.00	1.70
		Providing an additional worker in specific task usually performed by one individual	4.50	5.00	1.78
	Individuals getting hit by machinery during module production	Making it compulsory for everyone on the project to have Health & Safety certification before starting	6.75	7.00	0.47
		Adopting Kaizen concepts in all tasks	4.33	5.00	1.29
		Using the Last Planner System	4.00	4.00	1.10
		Having a team supervisor for each task station	5.58	5.00	0.93
	Having irregular data flow throughout the project	Using BIM platforms	6.17	6.00	0.98
		Using the Last Planner System	4.58	5.00	0.93
		Adopting decision making platforms at early stages	6.50	7.00	0.52
	Witnessing stick-built method under a roof	Using BIM platforms	5.75	6.00	1.60
		Using the Last Planner System	4.25	4.00	1.37
		Ensuring that the Engineer/Architect are well- versed in modular construction	6.42	7.00	1.04
		Using BIM platforms	5.67	6.00	1.49

	Experiencing poor communication between involved parties in the project	Using the Last Planner System	4.83	5.00	1.01
		Adopting decision making platforms at early stages	6.00	6.00	1.04
Governmental Support	Lacking interest from Government to opt for modular construction projects rather than conventional construction	Providing clear proof of previous cases and explaining concerned bodies	6.08	6.00	0.75
		Proposing vertical integration- selling buildings as products (e.g., cars)	4.92	5.00	1.30
		Providing more qualitative and educational content including basic details	6.00	6.00	0.94
	Unavailability of established rules country-wise focused on modular construction projects	Requesting for financial aid to enable qualified Engineers/ Architects to set building codes and standards specifically for modular projects	5.42	5.00	1.03
		Providing clear proof of previous cases and explaining concerned bodies	6.00	6.00	0.65
		Analyzing frameworks adopted by other countries and amend to suit current geographical demands	5.75	6.00	1.22

5.3.2 Delphi round 2

Table 10 below shows the mean, median, standard deviation values and the Relative Importance Index calculated from Delphi round 2 inputs comprising of 11 experts. *Appendix D* links to the detailed calculations.

Table 10: Mean, median, standard deviation and RII Delphi round 2

Risk Category	Risk Criteria	Risk Management Approach	Round 2 Mean value	Round 2 median	Round 2 standard deviation	Relative Importance Index (RII)

Supply chain	Lacking communication with local supply chain regarding highway rules and module size allowed	Using the Last Planner System	5.18	5.00	1.17	8.14
		Adopting Kanban technique	4.45	4.00	1.13	7.00
		Using Just in Time concept	4.09	4.00	1.45	6.43
		Using BIM platforms	6.00	6.00	0.89	9.43
	Witnessing clashes in the designed elements for modules	Using the Last Planner System	5.36	5.00	0.92	8.43
		Adopting Kanban technique	4.36	4.00	1.21	6.86
		Using Just in Time concept	3.82	4.00	1.08	6.00
		Using BIM platforms	6.36	6.00	0.67	10.00
		Opting for locally made materials and simplified designs	5.27	5.00	1.35	8.29
		Including tradesmen with experience instead of only designers	6.00	6.00	0.77	9.43
		Using Radio Frequency Identification tags	5.09	5.00	1.22	8.00
		Adopting Value Stream Mapping until project is delivered to client	5.55	5.00	1.13	8.71
	Having no early involvement of client and contractors in the project	Using the Last Planner System	3.45	3.00	1.69	5.43
		Using BIM platforms	4.73	5.00	2.00	7.43
		Adopting Value Stream Mapping until project is delivered to client	4.18	4.00	1.78	6.57
	Design team lacking experience and making use of unestablished design standards	Motivating Government for support and requesting grants	4.09	4.00	1.14	6.43
		Involving engineers and architects to tailor design standards based on experience	5.91	6.00	1.04	9.29
		Ensuring team members are qualified at or above a set academic/experience benchmark	6.27	6.00	0.79	9.86
	Dealing with multiple suppliers	Using the Last Planner System	5.18	5.00	0.98	8.14
		Adopting Kanban technique	5.00	5.00	1.48	7.86

Health & Safety		Using Just in Time concept	4.18	4.00	1.66	6.57
		Using BIM platforms	5.73	6.00	1.27	9.00
		Using Radio Frequency Identification tags	5.09	5.00	1.14	8.00
		Adopting Value Stream Mapping until project is delivered to client	5.36	5.00	1.03	8.43
	Workers having ergonomic injuries	Making it compulsory for everyone on the project to have Health & Safety certification before starting	5.73	6.00	1.27	9.00
		Adopting Kaizen concepts in all tasks	4.27	4.00	0.90	6.71
		Using the Last Planner System	4.18	4.00	0.87	6.57
		Having a team supervisor for each task station	5.18	6.00	1.17	8.14
		Providing an additional worker in specific task usually performed by one individual	4.45	4.00	1.21	7.00
		Using robotics for lifting and placing elements	6.36	6.00	0.50	10.00
		Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements	5.36	6.00	1.03	8.43
	Team members getting electrocuted during module manufacturing	Making it compulsory for everyone on the project to have Health & Safety certification before starting	6.27	6.00	0.90	9.86
		Adopting Kaizen concepts in all tasks	4.09	4.00	0.83	6.43
		Using the Last Planner System	3.82	4.00	1.33	6.00
		Having a team supervisor for each task station	4.91	5.00	1.58	7.71
		Providing an additional worker in specific task usually	4.64	5.00	1.63	7.29

		performed by one individual				
	Individuals getting hit by machinery during module production	Making it compulsory for everyone on the project to have Health & Safety certification before starting	6.73	7.00	0.47	10.57
		Adopting Kaizen concepts in all tasks	4.55	4.00	1.29	7.14
		Using the Last Planner System	4.18	4.00	0.75	6.57
		Having a team supervisor for each task station	5.55	6.00	0.82	8.71
Stakeholders	Having irregular data flow throughout the project	Using BIM platforms	6.27	6.00	0.65	9.86
		Using the Last Planner System	4.64	5.00	0.81	7.29
		Adopting decision making platforms at early stages	6.73	7.00	0.47	10.57
	Witnessing stick- built method under a roof	Using BIM platforms	6.36	6.00	0.67	10.00
		Using the Last Planner System	4.36	4.00	1.29	6.86
		Ensuring that the Engineer/Architect are well- versed in modular construction	6.64	7.00	0.50	10.43
	Experiencing poor communication between involved parties in the project	Using BIM platforms	6.00	6.00	1.00	9.43
		Using the Last Planner System	4.73	5.00	1.10	7.43
		Adopting decision making platforms at early stages	6.45	6.00	0.52	10.14
	Governmental Support	Lacking interest from Government to opt for modular construction projects rather than conventional construction				
		Providing clear proof of previous cases and explaining concerned bodies	6.00	6.00	0.63	9.43
		Proposing vertical integration- selling buildings as products (e.g., cars)	5.27	5.00	0.90	8.29
		Providing more qualitative and educational content including basic details	6.18	6.00	0.60	9.71

		Requesting for financial aid to enable qualified Engineers/ Architects to set building codes and standards specifically for modular projects	5.64	5.00	1.03	8.86
	Unavailability of established rules country-wise focused on modular construction projects	Providing clear proof of previous cases and explaining concerned bodies	6.18	6.00	0.60	9.71
		Analyzing frameworks adopted by other countries and amend to suit current geographical demands	6.00	6.00	1.41	9.43

5.3.3 Delphi control measures to eliminate bias

A successful Delphi method is achieved upon ensuring unbiased judgement from the meticulously put- together Delphi panel [44]. Biases can occur in methods such as collective unconscious, recency effect, and dominance. Bearing in mind these major biases -probable instances, this study's control measures ensure a bias-free Delphi method. Examples of such incentives considered throughout the Delphi process are, integrating feedbacks at the upcoming rounds to indicate specificity to the expert individually, thorough check if the expert has any outlying values which can occur due to personal experiences in specific situations, and at all instances keeping anonymity.

5.3.4 Experts preference in risk management approaches geographically- based

Upon receiving the second round Delphi scores from the panel of experts, the trend in preference of risk management approaches was deduced from the efficiency

scores that the panel allocated anonymously. The following sections describe the trends country wise.

5.3.4.1 United Arab Emirates (UAE)

With 27 % of the expert panel coming from the UAE, their preferences for risk management approaches integration according to efficiency in their past projects or experiences were analyzed. In the supply chain category, the highest score was allocated to ‘using BIM platforms’, ‘adopting Value Stream Mapping’, ‘ensuring team members are qualified to a certain level’ and ‘using RFID tags’. These portray financial abilities in the work culture to integrate the latest technologies while improving collaboration between team members. In the Health & safety risk category, compulsory health & safety certifications have shown the strong emphasis laid on opting for the qualified team from initial phases of projects. Leading to the Stakeholders risk category, ‘ensuring engineers/ architects are well versed in modular construction’ again supports the early integration of qualified team members. With ‘adopting decision making platforms at early stages’ forming part of the top-rated approaches, early phase planning and setting of a strong foundation before implementation in later stages is emphasized. As for governmental support risk category, ‘requesting financial aid to better allow engineers/ architects setting building codes and standards for specific modular projects’ is deem as more important and sets the path for efficient design stages.

5.3.4.2 Chile

9 % of the expert panel was based in Chile. To tackle supply chain risks, the preference was seen in opting for ‘using BIM platforms’, ‘adopting Kanban techniques’, ‘using Just in Time concepts’, ‘opting for locally made materials and simplified designs’, ‘using RFID tags’, ‘adopting Value Stream Mapping’, and ‘ensuring team members are

qualified to a certain level’. In comparison with the UAE, it appears that the provision of locally made materials is more accessible in Chile’s construction sector. Additionally, technological advances are noticeable with high efficiency scores allocated to BIM platforms usage as per the expert’s experience. In the Health & safety risk category, ‘compulsory health & safety certifications’, ‘providing an additional worker for certain tasks’, ‘using robotics for lifting and placing’, ‘having a team supervisor was opted as most efficient risk management approaches. Further, the governmental support category has a majority of risk management approach ranked the highest namely; ‘requesting financial aid to better allow engineers/ architects setting building codes and standards for specific modular projects’, ‘providing clear proof of success cases’, ‘providing more qualitative and educational content’, and ‘analyzing frameworks from other countries to amend and fit in the current geographical demand’. While Chile has a seismic-prone behavior, the properties of modular projects match the requirements to ensure safety of inhabitants. Hence, the risk management approaches for tackling governmental risks all depict high efficacy performance.

5.3.4.3 Australia

Australian experts formed 9 % of the Delphi panel of experts. Yet again, ‘using BIM platforms’ was rated the most efficient in tackling supply chain risks. Additionally, ‘including tradesmen with experience instead of only designers’, and “ensuring team members are qualified to a certain level’ were rated the top risk management approaches in this category. As for health & safety, ‘using robotics for lifting and placing’ and ‘compulsory health & safety certifications’ were rated as most efficient. This can be further supported by the meta-analysis in this study whereby it was deduced that the Australia modular construction sector is largely focused on automating the sector. Similar

to the UAE, ‘ensuring engineers/ architects are well versed in modular construction’, ‘adopting decision making platforms at early stages’, and ‘using BIM platforms’ are opted for to tackle stakeholders risks. The governmental support risk category similarly relates to ‘providing more qualitative and educational content’ and ‘analyzing frameworks from other countries to amend and fit in the current geographical demand’. This shows that more basic know-how is demanded for the governmental bodies to grasp the concepts of this efficient method of construction for eased implementation.

5.3.4.4 Canada

The Canadian modular construction sector has a better involvement in ‘using BIM platforms’ as the latter was rated the most efficient for all risk criteria in the risk category supply chain. Additionally, ‘including tradesmen with experience instead of only designers’ and ‘ensuring team members are qualified at or above a set academic/experience benchmark’ were the highest rated risk management approaches. Unlike the other countries mentioned, the use of lean principles was not ranked at the same efficiency level as BIM platforms. This depicts how different work cultures can integrate different risk management approaches according to their own capacity. In the health & safety risk category, ‘compulsory health & safety certifications’ was the top-rated risk management approach as seen for the other geographic regions as well. The stakeholders category showed ‘adopting decision making platforms at early stages’ result in the most efficient mitigation of risks. This supports the study’s aims and findings. Similar to Chile, ‘providing clear proof of success cases’, ‘providing more qualitative and educational content’, and ‘analyzing frameworks from other countries to amend and fit in the current geographical demand’ are among the most performance risk management approaches to enable governmental support.

5.3.4.5 United States of America (USA)

‘Ensuring team members are qualified at or above a set academic/experience benchmark’ was the highest rated risk management approach to tackle supply chain risks of modular construction according to the 27% Delphi expert proportion from the USA. This was followed by ‘adopting BIM platforms’ and it is deduced that starting off with the rightly qualified personnel will enable smooth integration of any platforms or technologies in the projects. As depicted from the previously mentioned countries, ‘compulsory health & safety certifications’ is scored as the best risk management approach in the health & safety category. The stakeholders category showed ‘adopting decision making platforms at early stages’ result in the most efficient mitigation of risks as also confirmed by the Canadian modular construction sector. The governmental risks are proven to be tackled with ‘providing clear proof of success cases’ which hence direct towards supported statements for eased integration in the construction sector.

5.3.4.6 United Kingdom (UK)

To handle risks in supply chain, 9% expert panel from the UK have rated ‘using BIM platforms’, ‘adopting Value Stream Mapping’, ‘ensuring team members are qualified at or above a set academic/experience benchmark’, ‘using Last Planner System’, ‘adopting Kanban techniques’, ‘using Just in Time concepts’, and ‘using RFID tags’ as the most efficient risk management approaches. With high scores for all of the mentioned risk management approach, it is seen that the UK modular construction sector has a large involvement in this method of construction given the ability to state efficiency performance accordingly. As for health & safety risks, ‘using robotics and Ergosystem for optimizing limb movements’ were categorized as most efficient. The health & safety of workers is prioritized in the UK construction sector and the cost incurred for ensuring

the latter seem to not be a hindrance in the path. As for stakeholders risks, ‘using BIM platforms’, ‘adopting decision making platforms at early stages’, and ‘ensuring engineers/architects are well versed in modular construction’, were the top rated risk management approaches depicting the crucial importance of early on preparation and meticulous recruitment of team members. Identical to Australia’s choices, the following risk management approaches have proven to be the most effective to handle governmental risks; ‘providing more qualitative and educational content’ and ‘analyzing frameworks from other countries to amend and fit in the current geographical demand’.

5.3.4.7 Turkey

As witnessed for majority of countries, ‘using BIM platforms’ is the most efficient risk management approach to ensure proper management of the supply chain phases. The equally rated risk management approach that mitigates supply chain risks was ‘Involving engineers and architects to tailor design standards based on experience’. This points out to the necessity for more thorough provisions in terms of the design standards of the Turkish modular construction sector since the latter is a newly integrated concept surging at a fast pace. In the health & safety risk management, ‘using robotics and Ergosystem for optimizing limb movements’, ‘compulsory health & safety certifications’, and ‘adopting Kaizen concepts in all tasks’ were the most efficiently rated approaches. Throughout the geographic analysis, the Turkish modular construction sector is the only one to emphasize on the importance of Kaizen concepts in tackling health & safety risks. This could be exemplary to other work cultures as a continuous improvement mindset shall benefit the holistic organizational levels of a project. Similar to the UK, ‘using BIM platforms’, ‘adopting decision making platforms at early stages’, and ‘ensuring engineers/architects are well versed in modular construction’, were the top- rated risk management

approaches to tackle stakeholders' risks. The governmental support risk category has depicted that 'requesting for financial aid to enable qualified Engineers/ Architects to set building codes and standards specifically for modular projects will tackle the risks efficiently. This indicates the high interest from the engineers and architects currently in Turkey to pave the way for a reliable modular construction sector with governmental support financially.

5.4 Reliability and validity tests

5.4.1 Standard deviation

The percentage decrease in standard deviation from round 1 and 2 ranged between 0 % and 56.36 %. With 0% decrease, it indicates experts have opted to not modify their initial submissions (round 2), while greater values show that a small standard deviation value was achieved hence indicating precision being reached. Individual change in standard deviations for each risk management approach is shown in *Appendix D*. For a clearer illustration the percentage decrease in standard deviation as per risk criteria is shown in Table 11 below with comparison from round 1 and 2.

Table 11: Percentage difference in standard deviation from Delphi round 1 and 2

Risk Category	Risk Criteria	Risk Management Approach	Round 1 standard deviation	Round 2 standard deviation	% Difference in SD for Round 1 and 2
Supply chain	Lacking communication with local supply chain regarding highway rules and module size allowed	Using the Last Planner System	7.15	4.64	35.18
		Adopting Kanban technique			
		Using Just in Time concept			
		Using BIM platforms			

	Witnessing clashes in the designed elements for modules	Using the Last Planner System	11.16	8.36	25.13
		Adopting Kanban technique			
		Using Just in Time concept			
		Using BIM platforms			
		Opting for locally made materials and simplified designs			
		Including tradesmen with experience instead of only designers			
		Using Radio Frequency Identification tags			
		Adopting Value Stream Mapping until project is delivered to client			
	Having no early involvement of client and contractors in the project	Using the Last Planner System	6.31	5.48	13.16
		Using BIM platforms			
		Adopting Value Stream Mapping until project is delivered to client			
	Design team lacking experience and making use of unestablished design standards	Motivating Government for support and requesting grants	3.98	2.97	25.42
		Involving engineers and architects to tailor design standards based on experience			
		Ensuring team members are qualified at or above a set academic/experience benchmark			
	Dealing with multiple suppliers	Using the Last Planner System	8.42	7.56	10.15
		Adopting Kanban technique			
		Using Just in Time concept			

Health & Safety		Using BIM platforms			
		Using Radio Frequency Identification tags			
		Adopting Value Stream Mapping until project is delivered to client			
	Workers having ergonomic injuries	Making it compulsory for everyone on the project to have Health & Safety certification before starting	9.32	6.96	25.30
		Adopting Kaizen concepts in all tasks			
		Using the Last Planner System			
		Having a team supervisor for each task station			
		Providing an additional worker in specific task usually performed by one individual			
		Using robotics for lifting and placing elements			
		Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements			
	Team members getting electrocuted during module manufacturing	Making it compulsory for everyone on the project to have Health & Safety certification before starting	7.63	6.27	17.81
		Adopting Kaizen concepts in all tasks			
		Using the Last Planner System			
		Having a team supervisor for each task station			

		Providing an additional worker in specific task usually performed by one individual			
	Individuals getting hit by machinery during module production	Making it compulsory for everyone on the project to have Health & Safety certification before starting	4.20	3.33	20.72
		Adopting Kaizen concepts in all tasks			
		Using the Last Planner System			
		Having a team supervisor for each task station			
Stakeholders	Having irregular data flow throughout the project	Using BIM platforms	2.46	1.92	21.71
		Using the Last Planner System			
		Adopting decision making platforms at early stages			
	Witnessing stick- built method under a roof	Using BIM platforms	4.20	2.47	41.30
		Using the Last Planner System			
		Ensuring that the Engineer/Architect are well- versed in modular construction			
	Experiencing poor communication between involved parties in the project	Using BIM platforms	3.51	2.63	25.18
		Using the Last Planner System			
		Adopting decision making platforms at early stages			
Governmental Support	Lacking interest from Government to opt for modular construction projects rather than conventional construction	Providing clear proof of previous cases and explaining concerned bodies	2.99	2.14	28.34
		Proposing vertical integration- selling buildings as products (e.g., cars)			

		Providing more qualitative and educational content including basic details			
	Unavailability of established rules country-wise focused on modular construction projects	Requesting for financial aid to enable qualified Engineers/ Architects to set building codes and standards specifically for modular projects	3.66	3.04	16.74
		Providing clear proof of previous cases and explaining concerned bodies			
		Analyzing frameworks adopted by other countries and amend to suit current geographical demands			

5.4.2 Cronbach's Alpha

The first Delphi round led to a Cronbach alpha value of 0.925. An excel sheet was then mounted with the mean values and sent to the same experts again for their final verdict of whether they stick to their initial scores or would like to make changes. The inputs from every expert remain anonymous throughout the Delphi study. This was the second stage of the Delphi method and while some experts made changes to their initial input, others were confident in their initial submission. This stage led to a Cronbach's alpha of 0.929. Both stages showed that the Cronbach's alpha values point to the consistency in the scores from experts. This depicts high reliability in the study's inputs. The Excel file used to calculate Cronbach Alpha values can be found in Appendix D.

5.4.3 Kendall's W

Table 12 below shows the Kendall's W for Delphi round 1 and 2 relating to each risk category. It was deduced that there was a level of agreement when it comes to risk management approaches in health and safety risk category. However, supply chain, stakeholder and governmental support have no strong agreement showing that different countries and suppliers come with different ways of work and not all risk management approaches apply similarly to the risk criteria. The possibility of low Kendall's coefficient is obvious during situations having a panel of greater than seven. However, low Kendall coefficient does not mean that there was no consensus achieved in the Delphi panel [121]. On another point, an increase in Kendall's W was seen for all risk categories from round 1 and 2, indicating the success in directing the Delphi panel towards consensus. Additionally, a decrease in standard deviation from round 1 and 2 from section 5.4.1 showed consensus was being achieved. The Excel sheet with detailed calculations can be reached from *Appendix D*.

Table 12: Kendall's W for Delphi round 1 and 2

Kendall's W Round 1			
Supply chain	Health & safety	Stakeholder	Governmental support
0.032	0.399	0.067	0.057
Kendall's W Round 2			
Supply chain	Health & safety	Stakeholder	Governmental support
0.037	0.426	0.092	0.062

5.5 The Analytical Hierarchy Process (AHP)

Table 13 to Table 16 indicate the ranked risk management approach for each risk category which was deduced from the AHP method. Hereby, the Delphi method results used in the AHP has enabled developing this reliable list of risk management approaches ranked according to efficiency. The Excel spreadsheet used for calculating the AHP scores of each risk management approach can be navigated from the *Appendix E*.

5.5.1 AHP interpretations for Supply chain risk category

Table 13 below indicates the ranked risk management approaches which are organized according to efficiency (i.e., 1: best option, 2: second best) for the risk category ‘Supply chain’. Upon analyzing the deductions from the AHP scores, ‘using BIM platforms’ ranked first as a risk management approach to deal with the overall supply chain risks in a modular construction project. The use of BIM platforms prepares a structured initiation phase whereby attributes from suppliers, designers, clients and contractors are gathered with involvement of all organizational levels. Furthermore, with the digital twin, accuracy is optimized, hence enabling efficient allowance of resources from the suppliers. The risk management approaches that follow are lean tools. These straighten the supply chain process by decreasing the unnecessary steps. This in turn eliminates excessive waste production, hence benefiting the cost aspect of a project. Additionally, the selection of a rightly qualified team is crucial for handling supply chain risks. These would ensure communication at technical levels remain doubt-free and organizational levels can come to consensus for each step taken along the way. Although some countries are not able to fully do so, the selection of local building materials largely diminishes risks in the supply chain category. There is no necessity to deal with the

shipping procedure and transportation which could affect material health given the different stations to go through.

Table 13: Ranked risk management approaches- Supply chain

Risk category	Risk management approaches	Rankings (1: best option)
Supply chain	Using BIM platforms	1
	Using Last Planner System	2
	Adopting Value Stream Mapping till project delivered to client	3
	Adopting Kanban technique	4
	Using Just in Time concept	5
	Ensure team members meet set qualification benchmarks	6
	Involving engineers and architects to tailor design standards based on experience	6
	Using Radio Frequency Identification tags	8
	Motivating Government for support & grant provisions	9
	Select tradesmen with experience instead of just recently qualified designers	10
	Simplified designs & choosing locally available materials	11

5.5.2 AHP interpretations for Health & safety risk category

Table 14 below indicates the ranked risk management approaches which are organized according to efficiency (i.e., 1: best option, 2: second best) for the risk category ‘health & safety’. The most efficient risk management approach in this category is to make it mandatory for the staffs to have a health & safety certification before starting off the project. This sets a benchmark on the know-how level of the individuals partaking in the project. Next is the allocation of a team supervisor at each workstation to monitor the overall progress and acknowledge any hazard reported by the team members. Similarly, lean tools have a great impact to mitigate the risks by shifting the work environment to a

more value-adding one. Providing an additional worker would help relieve the workload which would otherwise be performed by one individual. In fact, the latter can witness ergonomic risks due to improper movement and maneuvering of components. The use of robotics can act as substitute for many lifting and assembling purposes. Accordingly, the software Ergosystem simulates the best posture positions and handling techniques for workers. But these two risk management approaches are costly and would not be the most convenient option for a large number of projects.

Table 14: Ranked risk management approaches- Health & Safety

Risk category	Risk management approaches	Rankings (1: best option)
Health & safety	Making it compulsory for everyone on the project to have Health & Safety certification before starting	1
	Having a team supervisor for each task station	2
	Adopting Kaizen concepts in all tasks	3
	Using the Last Planner System	4
	Providing an additional worker in specific task usually performed by one individual	5
	Using robotics for lifting and placing elements	6
	Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements	7

5.5.3 AHP interpretations for Stakeholders risk category

Table 15 below indicates the ranked risk management approaches which are organized according to efficiency (i.e., 1: best option, 2: second best) for the risk category ‘Stakeholders’. The top ranked risk management approach is using BIM platforms, as

also witnessed in the ‘supply chain’ risk category. Additionally, the second-best risk management approach is the Last Planner System. These indicate the critical value of having a clear information flow with all organizational levels. The details with the digital twin model could be reached by every team member and the continuous meetings to discuss regarding project progress will enable achieving the promised deadline within the budget. Next is the adoption of decision-making platforms early on as these provide the team with multiple options that can be integrated in their projects to mitigate risks. However, another important aspect in this approach is the ability to evaluate and test the feasibility of the suggestions on the concerned project before actualizing it. These are followed by ensuring the engineers and architect are well- versed in modular construction specifically to not replicate the conventional construction techniques under a roof.

Table 15: Ranked risk management approaches- Stakeholders

Risk category	Risk management approaches	Rankings (1: best option)
Stakeholders	Using BIM platforms	1
	Using the Last Planner System	2
	Adopting decision making platforms at early stages	3
	Ensuring that the Engineer/Architect are well- versed in modular construction	4

5.5.4 AHP interpretations for Governmental Support risk category

Table 16 below indicates the ranked risk management approaches which are organized according to efficiency (i.e., 1: best option, 2: second best) for the risk category

‘governmental support’. The ranked risk management approaches are all based on the Delphi panel of experts who are geographically spread. This points to the fact that the risk management approaches are uniformized for most countries to consider. With the most efficient risk management approach being to provide more qualitative content, this indicates that educating the public about the beneficial aspects of modular construction is necessary. The provision of clear success evidence for previously done projects will set a strong foundation to gather the trust of the public in this sector. Being rather novel, the governmental bodies would demand reliable proposals to allocate grants. There are multiple countries such as the UAE, UK, and USA, who have demonstrated applaudable success in shifting toward modular construction. By analyzing frameworks adopted and make amendments based on the country criteria, the project teams could depict a promising path. The set-up of building codes and standards with specificity in the geographical area being targeted, will benefit the upcoming modular construction sector, and deems as a worthwhile initiative. While many developed countries depicted the franchising of modular projects, vertical integration is among the risk management approaches. For example, residential projects can be sold via the internet with all aspects listed like selling cars and other products. However, since many countries are not yet at the implementation stage, the vertical integration would apply to only a few areas.

Table 16: Ranked risk management approaches- Governmental Support

Risk category	Risk management approaches	Rankings (1: best option)
Governmental support	Providing more qualitative and educational content including basic details	1

	Providing clear proof of previous cases and explaining concerned bodies	2
	Requesting for financial aid to enable qualified Engineers/ Architects to set building codes and standards specifically for modular projects	3
	Analyzing frameworks adopted by other countries and amend to suit current geographical demands	3
	Proposing vertical integration- selling buildings as products (e.g., cars)	5

5.5.5 Reasoning mechanism of the AHP based decision making platform

As depicted in sections 5.5.1 – 5.5.4, the AHP based decision making process enabled achieving ranked risk management approaches for each risk criteria based on the uniformized weight scores given in this study. The ranked approaches are achieved according to their efficiency performance from the Delphi scores received by the experts. However, practitioners can reach to more precise rankings according to their project's criteria. This is achieved when the weight of the risk criteria is edited on the spreadsheet. In Figure 10, the initial rankings from uniformized weight (as performed in this study) for one risk category (i.e., health & safety) is shown as example. Furthermore, in Figure 11, modified risk criteria weight was applied to the spreadsheet and specifically ranked risk management approaches are then derived. Project managers or risk managers can apply the latter based on their project's demand.

RISK CATEGORY: HEALTH & SAFETY			RISK CRITERIA						RANKING NUMBER OF BEST APPROACHES (1:best option)
			C1	C2	C3				
			Workers having ergonomic injuries	Team members getting electrocuted during module manufacturing	Individuals getting hit by machinery during module production				
			Criteria weight						
0.33	0.33	0.33							
RISK MANAGEMENT APPROACHES/ ALTERNATIVES	A1	Making it compulsory for everyone on the project to have Health & Safety certification before starting	0.18	0.25	0.32	AHP SCORE A1	0.245735294	1	
	A2	Adopting Kaizen concepts in all tasks	0.12	0.17	0.23	AHP SCORE A2	0.168823529	3	
	A3	Using the Last Planner System	0.12	0.17	0.18	AHP SCORE A3	0.153823529	4	
	A4	Having a team supervisor for each task station	0.15	0.21	0.27	AHP SCORE A4	0.207279412	2	
	A5	Providing an additional worker in specific task usually performed by one individual	0.12	0.21		AHP SCORE A5	0.107573529	5	
	A6	Using robotics for lifting and placing elements	0.18			AHP SCORE A6	0.058235294	6	
	A7	Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements	0.15			AHP SCORE A7	0.048529412	7	

Figure 11: AHP generated ranked risk management approach with uniformized weight for risk criteria

RISK CATEGORY: HEALTH & SAFETY			RISK CRITERIA			weight of risk criteria was altered as an example to show that projects with different risk criteria can refer to the personalized ranked risk management approach		
			C1	C2	C3			
			Workers having ergonomic injuries	Team members getting electrocuted during module manufacturing	Individuals getting hit by machinery during module production			
			Criteria weight					
			0.8	0.1	0.1			
RISK MANAGEMENT APPROACHES/ALTERNATIVES	A1	Making it compulsory for everyone on the project to have Health & Safety certification before starting	0.18	0.25	0.32	AHP SCORE A1	0.197994652	1
	A2	Adopting Kaizen concepts in all tasks	0.12	0.17	0.23	AHP SCORE A2	0.133511586	4
	A3	Using the Last Planner System	0.12	0.17	0.18	AHP SCORE A3	0.128966152	5
	A4	Having a team supervisor for each task station	0.15	0.21	0.27	AHP SCORE A4	0.165753119	2
	A5	Providing an additional worker in specific task usually performed by one individual	0.12	0.21		AHP SCORE A5	0.11495098	7
	A6	Using robotics for lifting and placing elements	0.18			AHP SCORE A6	0.141176471	3
	A7	Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements	0.15			AHP SCORE A7	0.117647059	6

Figure 10: Newly ranked risk management approaches based on varied weight of risk criteria

5.6 Web-based risk management guide application

Further to section 5.5, the Delphi method findings and AHP results were integrated in an interactive web-based application. This user-friendly method will ensure that the target audience can use the latter during various project conditions and locations. After launching, the application was validated by industry experts for feasibility of usage and improvement scopes. The link to access the application is as follows and the QR code underneath leads to the application similarly. Further details on its development are shown in the sub-sections below.

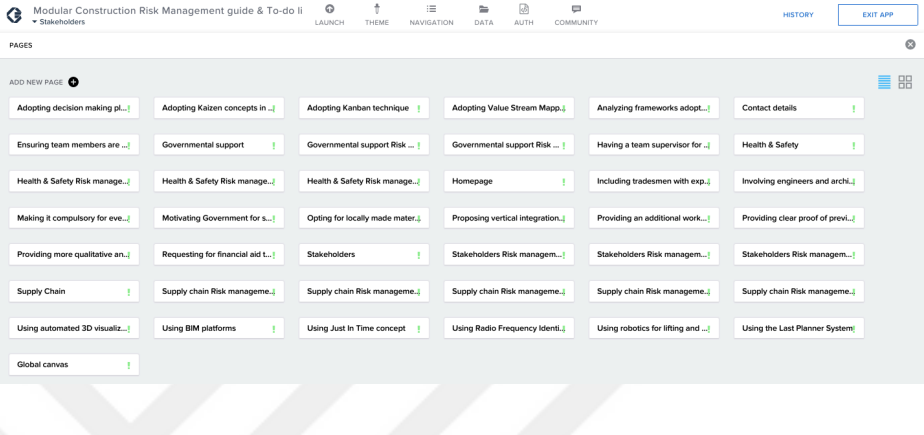
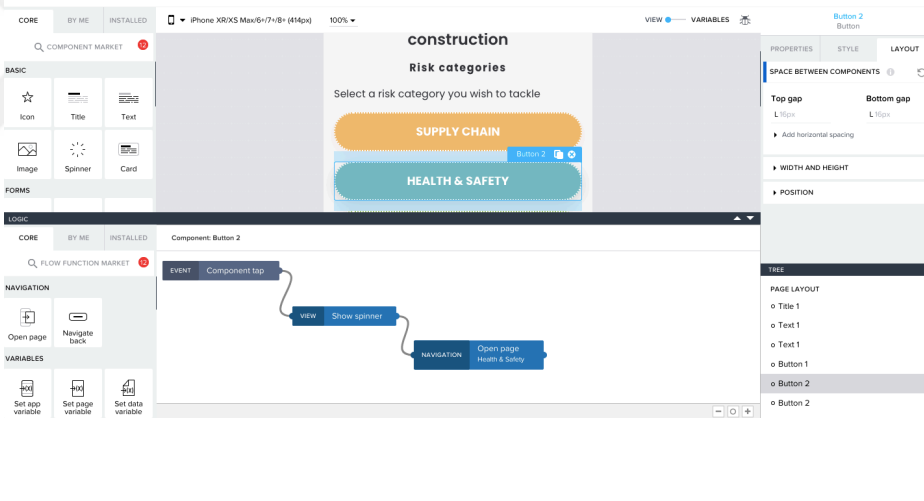
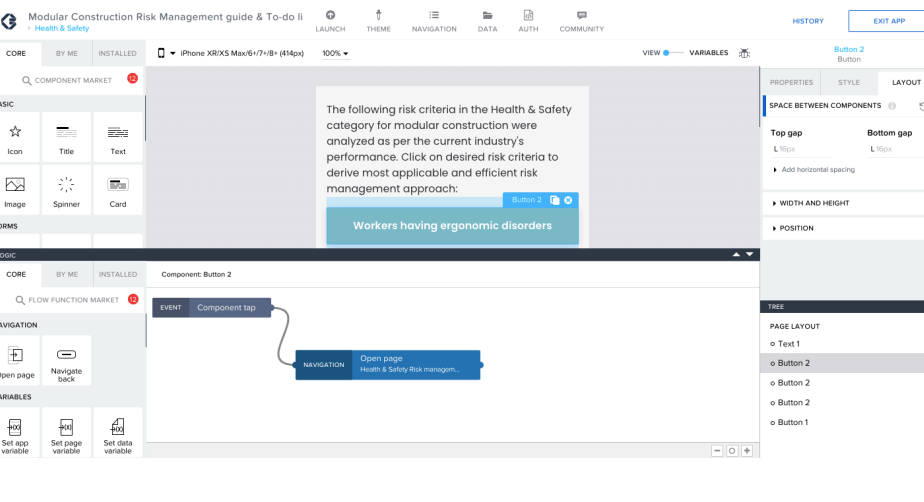
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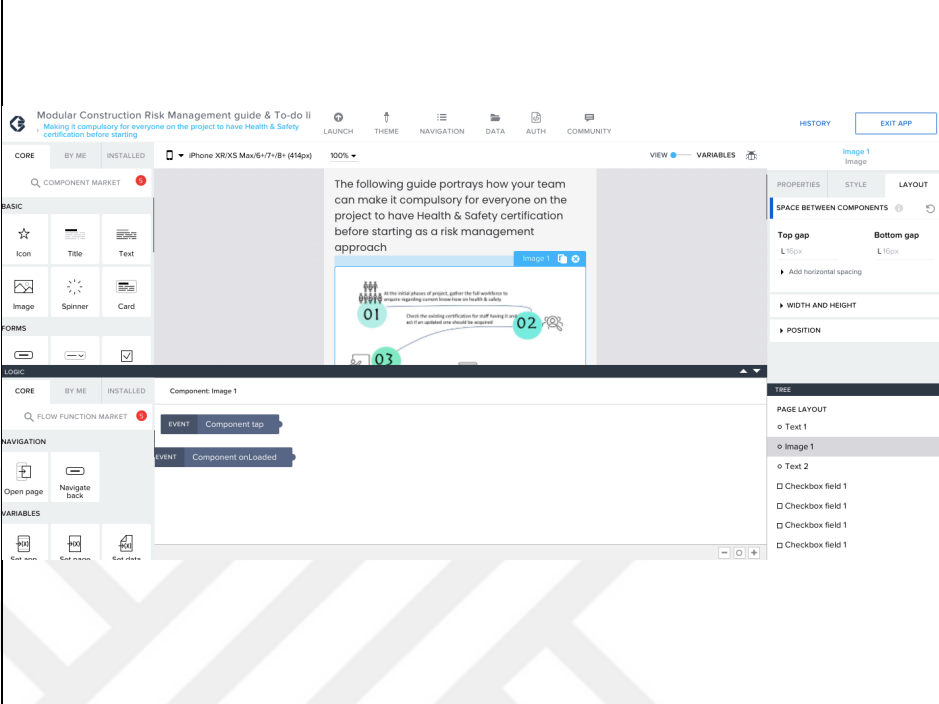
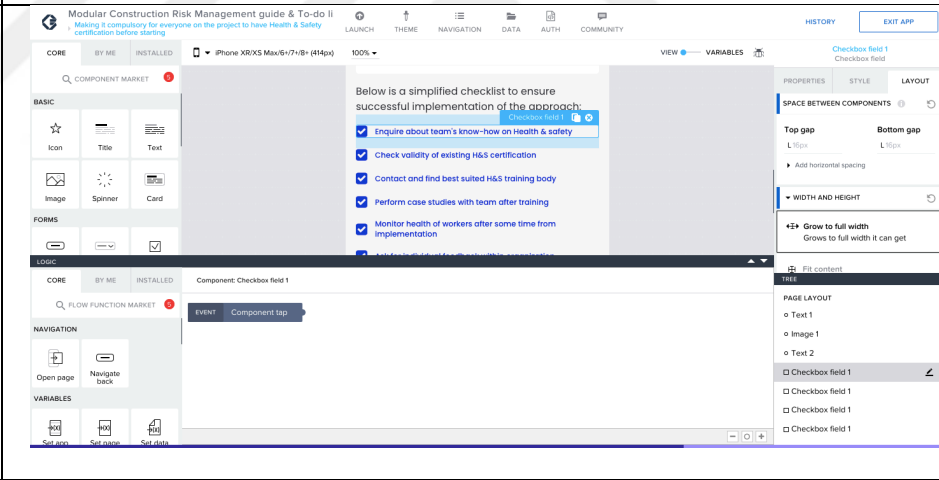
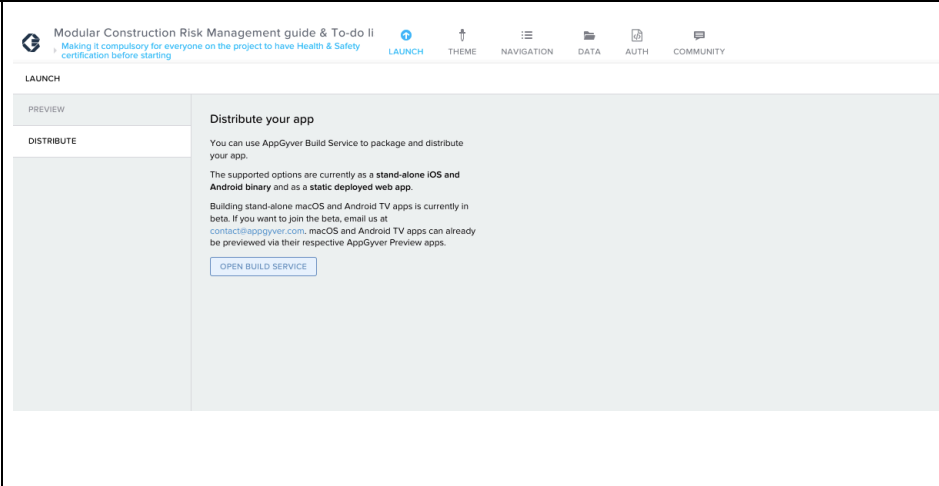


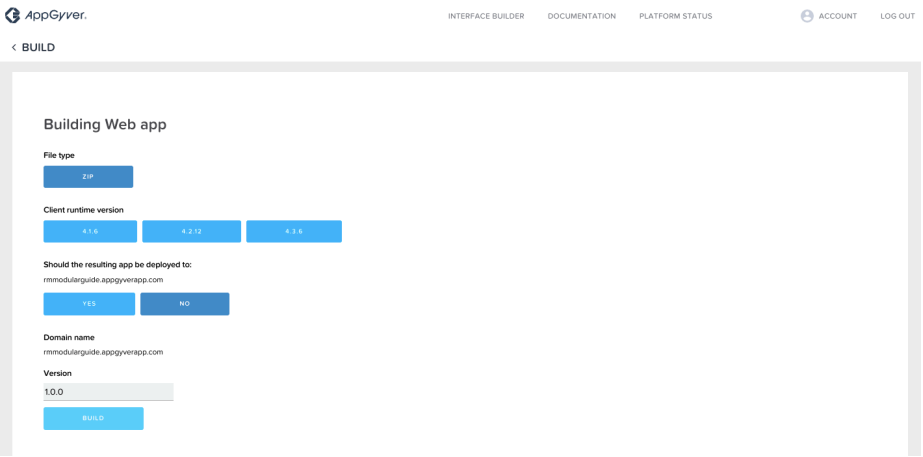
5.6.1 Mounting and launching the application

At this stage, a professional no-code platform called AppGyver was used to develop the interactive application. This platform has competent visual options and integrations. The most applaudable aspect was that every logic in the application is created visually and the user has full control on how to develop the application. Table 17 below shows the steps in detail on how the application was mounted and launched:

Table 17: Details for mounting and launching the application

Detailed steps	According to screenshot from platform
Step 1: All the pages forming part of the guide process are added individually with their according contents.	
Step 2: This shows the Homepage with the risk categories and the logic of the buttons. Once clicked, the next page with risk criteria for that specific risk category opens.	
Step 3: Upon clicking on a risk criteria, the next page to open up is risk management approaches. Hence in the logic of each risk criteria button, the page consisting of risk management approaches is connected.	

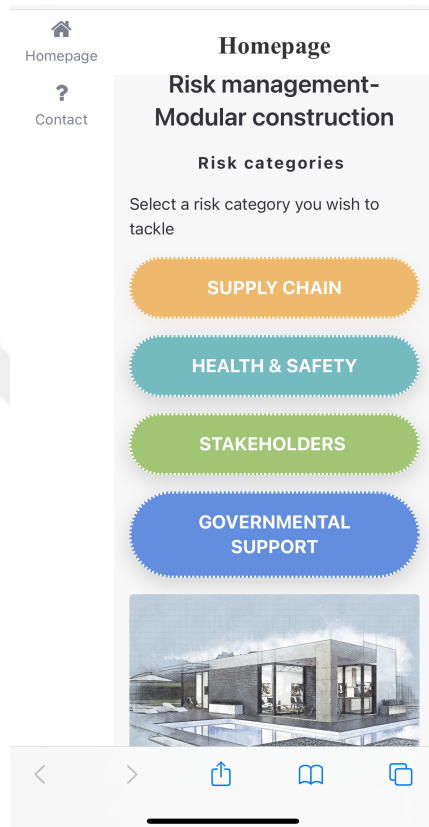
Step 4: Next step is to setup the button logic for each risk management approach. That is, upon clicking on a risk management approach, the implementation guide and to-do list shows up. As depicted below, the guide, which is inserted as a pdf, can be displayed.	
Step 5: As for the to-do list, these components are simply dropped on the same page with the relevant items typed in with the empty checkbox	
Step 6: After all pages are set, buttons connected and logic formed, the app could be launched. With the “open build service”, the version can be determined along with the app type (mobile, web based).	

Step 7: Web app was selected in this case and then it was built by picking up the domain name, and version along with the file type	
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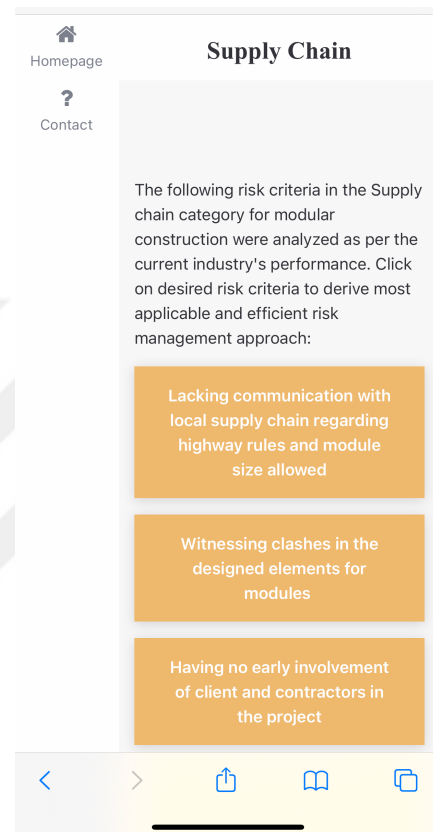
5.6.2 Application walkthrough

This application starts off early on with the user who picks which risk category to tackle. They are then provided with a list of risk criteria which are commonly faced in modular projects. The user decides which criteria to tackle based on what is applicable to their specific projects. The next step displays ranked risk management approaches according to efficiency. While selecting the risk management approach, a simple guide to implement the latter is made available followed by a to-do list. There is a freedom of choice that can be made between the proposed risk management approaches and the relevant user can pick based on capacity of the current team. Second best risk management approach is suggested similarly, and the guide is provided with a to-do list specific to implementing the latter. The steps in the application walkthrough are described below:

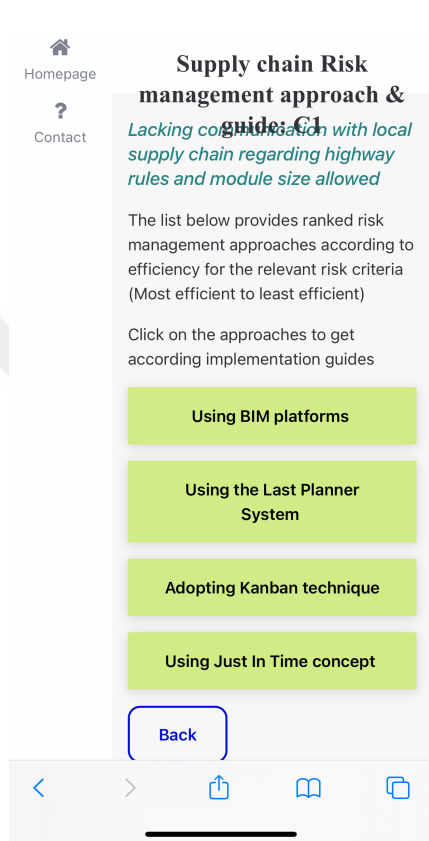
Step1: Once the link is opened, the Homepage is seen where the user can pick a risk category, they would like to tackle.



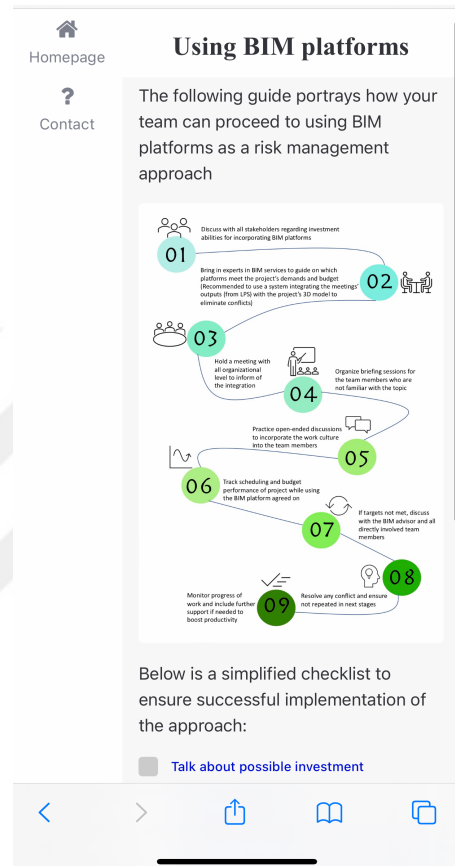
Step 2: As an example, Supply chain was picked, and the next page leads to risk criteria. According to the user's project, the latter can pick the risk criteria which applies most to the project.



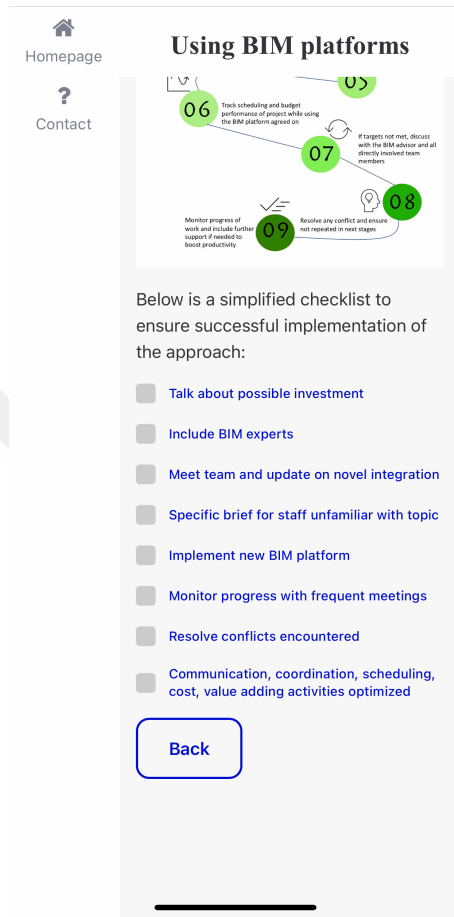
Step 3: In this example “lacking communication with local supply chain regarding highway rules and module size allowed” is picked. The Application directs the user to risk management approaches that are ranked according to efficiency performance. (i.e., first on the list: best option, second: second best option)



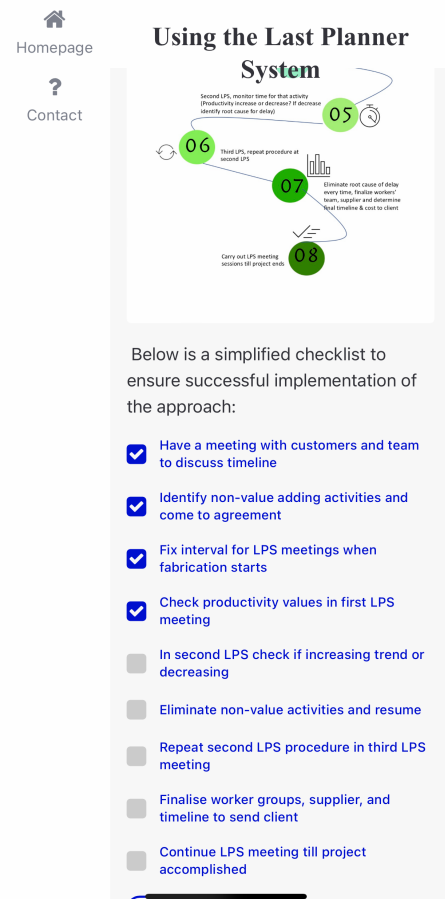
Step 4: As an example, clicking on the first risk management approach “Using BIM platforms”, a guide is provided which aids user to implement the latter in their project.



Step 5: Additionally, a to-do list will enable the user to determine if the capacity of the project team will successfully check off all boxes required to finalize the risk management approach.



Step 6: If the user cannot check off all boxes from the to-do list, then the second-best risk management approach can be referred to by going back to the previous page.



5.6.3 Validation of application

In order to test the feasibility and workability of the developed application, three experts were contacted via a virtual meeting to enable a walkthrough the application and entertain any questions they may have. Details of the experts and their relevant comments are shown in Table 18 below.

Table 18: Validation of application details

Expert No.	Expert current profession	Comments
1	Projects Risk management coordinator	• “An app that I would use in my projects” • “I would suggest users to use their own judgement too and test on their projects before implementing the risk management approaches as each project comes with different constraints and aims”
2	Studio director, Multi-family housing and modular construction	• “It is very easy to use and clear to achieve what we wish for during risk management” • “Maybe consider widening the risk category provided as options” • “Reliable platform since the efficiency ratings were from industry experts geographically distributed and involved in various stages of a modular project”
3	Head of operations-Modular construction	• “Good way of starting a project with the application guide” • “Further detail the logistic, design, demolition, facilities management phases” • “Geographical location matters for the governmental support risk category, investigate further into that to make it more specific”

CHAPTER VI

CONCLUSION

Despite the existing studies performed that aimed at exploring factors which are important for a productive modular construction sector, there is an insufficiency in research aiming to provide the sector with clear guidance on risk management at early phases. This research has analyzed the critical risk categories (i.e., supply chain, health & safety of workers, stakeholders, and governmental support) which seek urgent attention to direct the overall modular construction sector towards full capacity performance. A systematic literature review with 175 studies and meta-analysis enabled setting the foundation to pursue this quest. A two round-Delphi method was then performed with 11 experts. They participated in evaluating efficiency of each risk management approaches proposed for relevant risk criteria. These valuable scores were the foundation to initialize the Analytical Hierarchy Process. The inputs were validated and checked for reliability to move on further stages with tests such as percentage standard deviation decrease, Cronbach's alpha, and Kendall's coefficient of concordance (Kendall's W).

The Delphi method prominent findings have indicated the most feasible risk management approaches that are both efficient and applicable to the current modular construction sector. As such, it was noticed that experts have highly rated efficiency of risk management approaches such as 'using BIM platforms', 'compulsory health & safety certifications for all staff', and 'providing more qualitative and education content regarding basic concepts of modular construction'. Additionally lean principles such as Last Planner System, Value Stream Mapping, Just in Time, and Kaizen, were among the

top-rated risk management approaches. This will enable target audience to have a reliable reference prior to integrating these approaches to the projects.

The Analytical Hierarchy Process was performed to direct towards decision solving and indicating the most efficient risk management approach for each risk criteria. The AHP enabled thoroughly analyzing the Delphi panel's scores for each risk management approach to deduce the ranked options that would aid a decision maker in the risk category targeted. By considering the weight of the risk criteria, the AHP makes for a precise generation of AHP score calculated that narrows down to the ranked list of alternatives. For example, in the supply chain risk category, upon analyzing AHP scores for each alternative, the best risk management approach was determined as 'using BIM platforms', followed by 'using the Last Planner System'. Moreover, 'using BIM platforms' also proved to be the most efficient risk management approach in the stakeholder risk category. Additionally, target audience can rely on the validated outputs of this study to insert weight scores as per their project demands and retrieve most efficient risk management approach to be adopted with the AHP.

The deductions from AHP were integrated to form the logic of an interactive web-based application guide which was validated by experts in the industry. Upon selecting the risk management approach, next up on the application is implementation guides. The latter depicts steps on how to successfully implement the risk management approach selected. To aid the decision maker, a to-do list is provided. This shall enable analyzing if each element can be checked off, to get an idea of whether the current project can achieve those successfully before implementing the risk management approach. The project manager, stakeholders and organizational levels investigating the risk management of the projects concerned can proceed to evaluate the abilities of their project

to implement the ranked risk management approaches before actualizing to mitigate cost overruns and delays.

6.1 Contributions

The outcome of this study has paved a way to promote efficient risk management with early-on decision making for modular construction practitioners. This aspect leads to better timeline and budget management. The following list states the contributions of this research systematically:

- Trends in risk management approaches in the current modular construction sector
- Identifying the critical risk categories demanding urgent attention in the current modular construction sector
- Thoroughly portraying risk criteria and risk management approaches for the identified risk categories (diverse set of data for project managers, risk managers, and academicians)
- Delphi method validated score rating of the efficiency of each risk management approach according to the risk criteria
- Geographic preferences of risk management approach qualitatively explained according to Delphi scores received
- The AHP- based ranked risk management approach according to each risk criteria in this study, for general reference targeting project managers or risk managers
- Abilities to modify weight values of risk criteria (according to project being worked on) in the AHP- based spreadsheet that will provide newly ranked risk management approaches according to efficiency performance

- User-friendly web-based application for risk management guide in modular construction consisting of implementation guides and a to-do list

Overall, the validated findings in this research promotes continuous improvement aspects within the modular construction sector. The rich qualitative and quantitative insights fill up a portion of the process aiming to tackle the obstacles in the path of productivity achievement in modular construction.

6.2 Unique value

The unique value of this study consists of meticulously identifying the risk categories and criteria demanding major attention alongside the risk management approaches. Moreover, literature content was analyzed to map current trends in the risk management approaches for modular construction. A risk management guide platform with validated findings from the well-structured methodology also forms part of the distinctive value that this research pertains to. The research is a compatible element for the academic theories to rely on and for practitioners of the modular construction industry to inculcate in their work culture.

6.3 Future works

The findings of this study can be taken as benchmark to further enhance the upcoming research. Some future work aspects are as follows:

- Considering other risk categories such as operational risk, financial risk, and natural hazard risk,
- Further segmenting the risk criteria into different stages such as design, manufacturing, assembling, occupying, and demolishing,

- Providing a real-time case study which implements the tool developed to showcase percentage improvement in overall project upon usage,
- Incorporating different types of modular construction projects while evaluating the risk criteria and management approaches.

6.4 Limitations

This study has meticulously planned each stage towards achieving the goals. The limitation of this study is including Delphi experts from UAE, US, UK, Chile, Turkey, Canada only. Despite the spread in geographic location, having an expert from other countries pursuing modular construction would direct towards a more precise generalization of outputs. This limitation is not critically affecting the results in a negative manner. However, upon resolving the latter, studies can expect highly specific outcomes.

APPENDIX A

SEMI-STRUCTURED VIRTUAL INTERVIEW QUESTIONS AND OPEN-ENDED QUESTIONNAIRE

This section consists of information on the interviews and questionnaires for an initial data collection to be used at the upcoming stages of the research. The interviews questions asked are as follows:

- How is the current workflow from the manufacturing location to the site
- What constraints are faced dealing with suppliers (supply chain risks)
- What are some risks faced at the design phase
- How do you ensure tackling risks that hinders quality
- How do you introduce to the team a risk management approach that has been picked for the project (educating, integrating, monitoring progress after applying)
- What are the risk management approaches used to mitigate scheduling risks (Are you familiar with RFID tags, lean methods)
- What are the most used lean principles in your projects
- Health and safety risks that can be encountered in factory or on installation site
- How does the team coordinate tasks shared between stakeholders
- What would you recommend as risk management approach for tackling governmental risks faced in the modular sector

The open- ended questionnaire link can be found below:

<https://forms.gle/mTKTaXyiEJgrHzy7>

APPENDIX B

DELPHI QUESTIONNAIRE

Figure 12 below shows the main page of the platform (Jotform) whereby Delphi round 1 questionnaire was designed and published to be sent to the experts. Figure 13 shows an example of how risk categories were displayed with relevant risk criteria and management approaches. With the scale of 1-7 (where 1 referred to “Not efficient” while 7 referred to “Highly efficient”), experts rated the efficiency of the risk management approach concerned according to the risk criteria targeted. The link below gives a preview of the form’s accessibility:

<https://form.jotform.com/211983311474960>

The screenshot displays the Jotform 'Form Builder' interface for a questionnaire titled 'Delphi Stage 1: Risk management approaches in modular construction'. The form is designed by Sabah Khodabocus, a graduate student in Civil Engineering at Özyeğin University. The form's main content includes a title 'Delphi Stage 1' and a description: 'Rating efficiency of risk management approaches according to risk criteria provided for each risk category analysed'. Below this, there are input fields for 'Full Name' (split into First Name and Last Name) and 'Title'. The footer shows page navigation (PAGE 1, PAGE 2, PAGE 3, THANK YOU PAGE) and an 'Add New Page' button.

Figure 12: Main page of Jotform platform used for developing Delphi questionnaire

(1) RISK CATEGORY: SUPPLY CHAIN
IN MODULAR CONSTRUCTION

CRITERIA 1: Lacking communication with local supply chain regarding highway rules and module size allowed

Using the Last Planner System *

1

2

3

4

5

6

7

Not efficient

Highly efficient

Adopting Kanban technique *

1

2

3

4

5

6

7

Not efficient

Highly efficient

Using Just In Time concept *

1

2

3

4

5

6

7

Not efficient

Highly efficient

Jotform

Now create your own Jotform - It's free!

Create your own Jotform

Figure 13: Example of rating section for risk management approaches

APPENDIX C

DELPHI ROUND 2 FORM SAMPLE

Table 19 below shows a sample of the form sent to the experts during round 2. This consisted of their initial score submissions, mean value from round 1 and a slot for amendments if desired.

Table 19: Example of form sent to expert for Delphi round 2

Risk Category	Risk Criteria	Risk Management Approach	Your submitted Score rating	Mean value (From Delphi stage 1)	Your reconsidered Score rating (if any)
Supply chain	Lacking communication with local supply chain regarding highway rules and module size allowed	Using the Last Planner System	5	5	
		Adopting Kanban technique	6	4	
		Using Just In Time concept	4	4	
		Using BIM platforms	5	6	
	Witnessing clashes in the designed elements for modules	Using the Last Planner System	5	5	
		Adopting Kanban technique	4	4	
		Using Just In Time concept	2	4	
		Using BIM platforms	7	6	
		Opting for locally made materials and simplified designs	4	5	
		Including tradesmen with experience instead of only designers	7	6	
		Using Radio Frequency Identification tags	6	5	
		Adopting Value Stream Mapping until project is delivered to client	5	6	
	Having no early involvement of client and contractors in the project	Using the Last Planner System	4	3	
		Using BIM platforms	5	4	
		Adopting Value Stream Mapping until project is delivered to client	6	4	
	Design team lacking experience and making use of	Motivating Government for support and requesting grants	4	4	

	unestablished design standards	Involving engineers and architects to tailor design standards based on experience	5	6	
		Ensuring team members are qualified at or above a set academic/experience benchmark	7	6	
	Dealing with multiple suppliers	Using the Last Planner System	6	5	
		Adopting Kanban technique	5	5	
		Using Just In Time concept	4	4	
		Using BIM platforms	3	6	
		Using Radio Frequency Identification tags	5	5	
		Adopting Value Stream Mapping until project is delivered to client	4	5	
	Workers having ergonomic injuries	Making it compulsory for everyone on the project to have Health & Safety certification before starting	6	6	
		Adopting Kaizen concepts in all tasks	5	4	
		Using the Last Planner System	4	4	
		Having a team supervisor for each task station	6	5	
		Providing an additional worker in specific task usually performed by one individual	5	4	
		Using robotics for lifting and placing elements	7	6	
		Using automated 3D visualization platforms like ErgoSystem for optimizing safer limb movements	5	6	
Health & Safety	Team members getting electrocuted during module manufacturing	Making it compulsory for everyone on the project to have Health & Safety certification before starting	7	6	
		Adopting Kaizen concepts in all tasks	6	4	
		Using the Last Planner System	4	4	
		Having a team supervisor for each task station	6	5	
		Providing an additional worker in specific task usually performed by one individual	7	5	
	Individuals getting hit by machinery during module production	Making it compulsory for everyone on the project to have Health & Safety certification before starting	7	7	
		Adopting Kaizen concepts in all tasks	6	4	

		Using the Last Planner System	4	4	
		Having a team supervisor for each task station	6	6	
Stakeholders	Having irregular data flow throughout the project	Using BIM platforms	7	6	
		Using the Last Planner System	3	5	
		Adopting decision making platforms at early stages	6	7	
	Witnessing stick-built method under a roof	Using BIM platforms	6	6	
		Using the Last Planner System	4	4	
		Ensuring that the Engineer/Architect are well- versed in modular construction	7	6	
	Experiencing poor communication between involved parties in the project	Using BIM platforms	5	6	
		Using the Last Planner System	6	5	
		Adopting decision making platforms at early stages	7	6	
Governmental Support	Lacking interest from Government to opt for modular construction projects rather than conventional construction	Providing clear proof of previous cases and explaining concerned bodies	6	6	
		Proposing vertical integration- selling buildings as products (e.g; cars)	3	5	
		Providing more qualitative and educational content including basic details	7	6	
	Unavailability of established rules country-wise focused on modular construction projects	Requesting for financial aid to enable qualified Engineers/ Architects to set building codes and standards specifically for modular projects	5	5	
		Providing clear proof of previous cases and explaining concerned bodies	5	6	
		Analyzing frameworks adopted by other countries and amend to suit current geographical demands	7	6	

APPENDIX D

STANDARD DEVIATION, RII, CRONBACH'S ALPHA, KENDALL'S COEFFICIENT OF CONCORDANCE (W)

The link below leads to the Excel file with calculations including standard deviation, RII, Cronbach's alpha and Kendall's W:

https://docs.google.com/spreadsheets/d/1JW2CxUkL_usxV7s_b8Go7J6w_VWej_kz/edit?usp=sharing&ouid=117707787678457255820&rtpof=true&sd=true

APPENDIX E

THE ANALYTICAL HIERARCHY PROCESS (AHP)

The link below leads to the Excel file with calculations for the AHP:

https://docs.google.com/spreadsheets/d/1zEFdm7oE4IYTebjJV41hdNwi7X_8PgAu/edit?usp=sharing&ouid=117707787678457255820&rtpof=true&sd=true

BIBLIOGRAPHY

- [1] Borjegahleh, R. M. and Sardroud, J. M, “Approaching Industrialization of Buildings and Integrated Construction Using Building Information Modeling”, *Procedia Engineering*, vol. 164, pp. 534–541, Dec. 2016, doi: 10.1016/j.proeng.2016.11.655.
- [2] Jin, R. *et al*, “A holistic review of off-site construction literature published between 2008 and 2018”, *Journal of Cleaner Production*, vol. 202, pp. 1202–1219, Aug. 2018, doi: 10.1016/j.jclepro.2018.08.195.
- [3] Zhang, Y. *et al*, “Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance”, *Journal of Construction Engineering and Management*, vol. 146(9), p. 04020116, Jul. 2020, doi: 10.1061/(asce)co.1943-7862.0001909.
- [4] Wuni, I. Y., Shen, G. Q. P. and Mahmud, A. T, “Critical risk factors in the application of modular integrated construction: a systematic review”, *International Journal of Construction Management*, vol. 22, pp.133-147, May 2019, doi: 10.1080/15623599.2019.1613212.
- [5] Gan, X., Chang, R. and Wen, T, “Overcoming barriers to off-site construction through engaging stakeholders: A two-mode social network analysis”, *Journal of Cleaner Production Elsevier Ltd*, vol. 201, pp. 735–747, Aug. 2018, doi: 10.1016/j.jclepro.2018.07.299.
- [6] Sutrisna, M. and Goulding, J, “Managing information flow and design processes to reduce design risks in offsite construction projects”, *Engineering, Construction and Architectural Management*, vol. 26(2), pp. 267–284, Jun. 2018, doi: 10.1108/ECAM-11-2017-0250.
- [7] Wuni, I. Y. and Shen, G. Q, “Critical success factors for modular integrated construction projects: a review”, *Building Research & Information*, vol. 48(7), pp. 763–784, Sep. 2019, doi: 10.1080/09613218.2019.1669009.
- [8] Wuni, I.Y. and Shen, G. Q, “Critical success factors for management of the early stages of prefabricated prefinished volumetric construction project life cycle”, *Engineering, Construction and Architectural Management*, vol. 27(9), pp. 2315–2333, Sep. 2019, doi: 10.1108/ECAM-10-2019-0534.
- [9] Wuni, Ibrahim Yahaya and Shen, G. Q, “Barriers to the adoption of modular integrated construction: Systematic review and meta-analysis, integrated conceptual framework, and strategies”, *Journal of Cleaner Production*, vol. 249, p. 119347, Mar. 2020, doi: 10.1016/j.jclepro.2019.119347.
- [10] Olawumi, T. O. *et al*, “Automating the modular construction process: A review of digital technologies and future directions with blockchain technology”,

Journal of Building Engineering Elsevier Ltd, vol. 46, p. 103720, Apr. 2021, doi: 10.1016/j.jobbe.2021.103720.

- [11] Li, H. X. *et al*, “Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation”, Canadian Journal of Civil Engineering, vol. 40(12), pp. 1184–1195, Jun. 2013, doi: 10.1139/cjce-2013-0013.
- [12] Sun, Y. *et al*, “Constraints hindering the development of high-rise modular buildings”, Applied Sciences (Switzerland), vol. 10(20), pp. 1–20, Oct. 2020, doi: 10.3390/app10207159.
- [13] Sharmila, T. and Sangeetha, R. K, “Study on improving project productivity with modular construction”, International Journal of Applied Engineering Research, vol. 10(13), pp. 11689–11696, Jan. 2015.
- [14] Abdul Nabi, M. and El-adaway, I. H, “Understanding the Key Risks Affecting Cost and Schedule Performance of Modular Construction Projects”, Journal of Management in Engineering, vol. 37(4), p. 04021023, Mar. 2021, doi: 10.1061/(ASCE)ME.1943-5479.0000917.
- [15] Abdul Nabi, M. and El-Adaway, I. H, ‘Risk-Based Approach to Predict the Cost Performance of Modularization in Construction Projects’, Journal of Construction Engineering and Management, vol. 147(10), Oct. 2021, doi: 10.1061/(ASCE)CO.1943-7862.0002159.
- [16] Li, X., Li, Z. and Wu, G, “Modular and Offsite Construction of Piping: Current Barriers and Route”, Applied Sciences, vol. 7(6), p. 547, May 2017, doi: 10.3390/app7060547.
- [17] Lee, J.-S. and Kim, Y.-S, “Analysis of cost-increasing risk factors in modular construction in Korea using FMEA”, KSCE Journal of Civil Engineering, vol. 21(6), pp. 1999–2010, Nov. 2016, doi: 10.1007/s12205-016-0194-1.
- [18] Shen, K. *et al*, “Research on the rework risk core tasks in prefabricated construction in China”, Engineering, Construction and Architectural Management, vol. 28(10), pp. 3299–3321, Jan. 2021, doi: 10.1108/ECAM-07-2020-0521.
- [19] Liu, Q., Ye, G. and Feng, Y, “Workers’ safety behaviors in the off-site manufacturing plant”, Engineering, Construction and Architectural Management, vol. 27(3), pp. 765–784, Oct. 2019, doi: 10.1108/ECAM-03-2019-0136.
- [20] Costantino, F. *et al*, “New and Emerging Hazards for Health and Safety within Digitalized Manufacturing Systems”, Sustainability, vol. 13(19), p. 10948, Oct. 2021, doi: 10.3390/su131910948.
- [21] Jeong, G. *et al*, “Analysis of safety risk factors of modular construction to identify accident trends”, Journal of Asian Architecture and Building

Engineering, vol. 21(3), pp 1040- 1052, Feb. 2021, doi: 10.1080/13467581.2021.1877141.

- [22] Cho, K. *et al*, “Schedule Delay Leading Indicators in Precast Concrete Construction Projects: Qualitative Comparative Analysis of Korean Cases”, *Journal of Management in Engineering*, vol. 37(4), Jul. 2021, doi: 10.1061/(ASCE)ME.1943-5479.0000915.
- [23] Ferdous, W. *et al*, “New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review”, *Engineering Structures*, vol. 183, pp. 883–893, Mar. 2019, doi: 10.1016/j.engstruct.2019.01.061.
- [24] Wong, P. S. P., Whelan, B. and Holdsworth S, “Are contractors ready for greater use of prefabrication in projects? An empirical analysis on the role of unlearning and counter-knowledge”, *International Journal of Construction Management*, vol. 21(4), pp. 353–368, Dec. 2018, doi: 10.1080/15623599.2018.1539160.
- [25] Li, M. *et al*, “Research on investment risk management of Chinese prefabricated construction projects based on a system dynamics model”, *Buildings*, vol. 7(3), p. 83, Sep. 2017, doi: 10.3390/buildings7030083.
- [26] Hsu, P.-Y., Aurisicchio, M. and Angeloudis, P, “Risk-averse supply chain for modular construction projects”, *Automation in Construction*, vol. 106, p. 102898, Oct. 2019, doi: 10.1016/j.autcon.2019.102898.
- [27] Ismail, Z.-A. Bin, “Hybrid intelligent vehicle system for managing construction supply chain in precast concrete building construction projects”, *World Journal of Engineering*, vol. 18(4), pp. 538–546, Oct. 2020, doi: 10.1108/WJE-08-2020-0361.
- [28] Darko, A. *et al*, “Building information modeling (BIM)-based modular integrated construction risk management – Critical survey and future needs”, *Computers in Industry Elsevier B.V.*, vol. 123, p. 103327, Dec. 2020, doi: 10.1016/j.compind.2020.103327.
- [29] Li, C. Z. *et al*, “Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction”, *Journal of Cleaner Production*, vol. 165, pp. 1048–1062, Nov. 2017, doi: 10.1016/j.jclepro.2017.07.156.
- [30] Zhou, J. X. *et al*, “Customization of on-site assembly services by integrating the internet of things and BIM technologies in modular integrated construction”, *Automation in Construction*, vol. 126, p. 10366, Jun. 2021, doi: 10.1016/j.autcon.2021.103663.
- [31] Rashid, K. M. and Louis, J, “Activity identification in modular construction using audio signals and machine learning”, *Automation in Construction*, vol. 119, p. 103361, Nov. 2020, doi: 10.1016/j.autcon.2020.103361

- [32] Li, L. *et al*, “A review of global lean construction during the past two decades: analysis and visualization”, *Engineering, Construction and Architectural Management*, vol. 26(6), pp. 1192–1216, Apr. 2019, doi: 10.1108/ECAM-03-2018-0133.
- [33] Court, P. F. *et al*, “Modular assembly with postponement to improve health, safety, and productivity in construction”, *Practice Periodical on Structural Design and Construction*, vol. 14(2), pp. 81–89, May 2009, doi: 10.1061/(ASCE)1084-0680(2009)14:2(81).
- [34] Van der Ham, M. and Opdenakker R, “Overcoming process-related barriers in modular high-rise building projects”, *International Journal of Construction Management*, pp. 1–11, Nov. 2021, doi: 10.1080/15623599.2021.2007593.
- [35] Rausch, C. *et al*, “Monte Carlo simulation for tolerance analysis in prefabrication and offsite construction”, *Automation in Construction*, vol. 103, pp. 300–314, Jul. 2019, doi: 10.1016/j.autcon.2019.03.026.
- [36] Hussein, M. *et al*, “Modelling in off-site construction supply chain management: A review and future directions for sustainable modular integrated construction”, *Journal of Cleaner Production*, vol. 310, Aug. 2021, doi: 10.1016/j.jclepro.2021.127503.
- [37] Hussein, M. and Zayed, T, “Crane operations and planning in modular integrated construction: Mixed review of literature”, *Automation in Construction*, vol. 122, p. 103466, Feb. 2021, doi: 10.1016/j.autcon.2020.103466.
- [38] Lu, W. *et al*, “Searching for an optimal level of prefabrication in construction: An analytical framework”, *Journal of Cleaner Production*, vol. 201, pp. 236–245, Nov. 2018, doi: 10.1016/j.jclepro.2018.07.319.
- [39] Zhu, H. *et al*, “The exploration of the life-cycle energy saving potential for using prefabrication in residential buildings in China”, *Energy and Buildings*, vol. 166, pp. 561–570, May 2018, doi: 10.1016/j.enbuild.2017.12.045.
- [40] Saad, S. *et al*, “A qualitative conceptual framework to tackle skill shortages in offsite construction industry: a scientometric approach”, *Engineering, Construction and Architectural Management*, ahead-of-p(ahead-of-print), Sep. 2021, doi: 10.1108/ECAM-04-2021-0287.
- [41] Li, X. *et al*, “RBL-PHP: Simulation of Lean Construction and Information Technologies for Prefabrication Housing Production”, *Journal of Management in Engineering*, vol. 34(2), Mar. 2018, doi: 10.1061/(ASCE)ME.1943-5479.0000577.
- [42] Donthu, N. *et al*, “How to conduct a bibliometric analysis: An overview and guidelines”, *Journal of Business Research Elsevier Inc.*, vol.133, pp. 285–296, Sep. 2021, doi: 10.1016/j.jbusres.2021.04.070.

- [43] Hansen, C., Steinmetz, H. and Block J, “How to conduct a meta-analysis in eight steps: a practical guide”, *Management Review Quarterly Springer International Publishing*, vol. 72(1), pp. 1–19, Nov. 2021, doi: 10.1007/s11301-021-00247-4.
- [44] Hallowell, M. R. and Gambatese, J. A, “Qualitative Research: Application of the Delphi Method to CEM Research”, *Journal of Construction Engineering and Management*, vol. 136(1), pp. 99–107, Jan. 2010, doi: 10.1061/(asce)co.1943-7862.0000137.
- [45] Sourani, A. and Sohail, M, “The Delphi Method: Review and Use in Construction Management Research”, *International Journal of Construction Education and Research Routledge*, vol. 11(1), pp. 54–76, Aug. 2014, doi: 10.1080/15578771.2014.917132.
- [46] Green, P. E., & Rao, V. R, “Rating scales and information recovery: How many scales and response categories to use?” *Journal of Marketing*, vol. 34, pp. 33-39, Jul. 1970, doi: 10.1177/002224297003400307.
- [47] Symonds, P . M, “On the loss of reliability in ratings due to coarseness of the scale”, *Journal of Experimental Psychology*, vol. 7, pp. 456-461, Dec. 1924, doi: 10.1037/H0074469.
- [48] McKelvie, S. J, “Graphic rating scales: How many categories?” *British Journal of Psychology*, vol. 69, pp. 185-202, May 1978, doi: 10.1111/j.2044-8295.1978.tb01647.x.
- [49] Wu, P. *et al*, “Perceptions towards risks involved in off-site construction in the integrated design & construction project delivery”, *Journal of Cleaner Production Elsevier Ltd*, vol. 213, pp. 899–914, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.226.
- [50] Bland J, Altman D, “Statistics notes: Cronbach's alpha”, *BMJ*, vol. 314, p. 572, Feb. 1997, doi: 10.1136/bmj.314.7080.572.
- [51] DeVellis, R.F, “Scale Development: Theory and Applications”, 2nd ed., Thousand Oaks, CA, SAGE Publications, Inc., 2003
- [52] Cronbach, L. J, “Coefficient alpha and the internal structure of tests”, *Psychometrika*, vol.16(3), pp. 297–334, Sep. 1951, doi: 10.1007/BF02310555
- [53] Yaokumah, W., Omane-Antwi, B. B. and Asante-Offei, K. O, “Critical success factors of strategic information systems planning: a Delphi approach”, *Kybernetes*, Jan. 2022, doi: 10.1108/K-05-2021-0370.
- [54] Ameyaw, E.E., Hu, Y., Shan, M., Chan, A.P.C. and Le, Y, “Application of Delphi method in construction engineering and management research: a quantitative perspective”, *Journal of Civil Engineering and Management*, Vol. 22

No. 8, pp. 991-1000, Jan. 2016, doi: 10.3846/13923730.2014.945953.

- [55] Siegel, S, “Nonparametric Statistics for the Behavioral Sciences”, 1st ed., New York, McGraw-Hill, 1956
- [56] Siegel, S., and Castellan, N. J., Jr, “Nonparametric Statistics for the Behavioral Sciences”, 2nd ed., New York, McGraw-Hill, 1988
- [57] Legendre, P, “Species associations: The Kendall coefficient of concordance revisited”, *Journal of Agricultural, Biological, and Environmental Statistics*, vol. 10(2), pp. 226–245, Jun 2005, doi: 10.1198/108571105X46642.
- [58] Evangelos Traintaphyllou, “A Comparative Study Applied Optimization”, Louisiana, SPRINGER-SCIENCE+BUSINESS MEDIA B.V, vol.44, Jan. 2000, doi: 10.1007/978-1-4757-3157-6.
- [59] Ameyaw, E. E. *et al*, “Application of Delphi method in construction engineering and management research: A quantitative perspective”, *Journal of Civil Engineering and Management*, vol. 22(8), pp. 991–1000, Jan. 2016, doi: 10.3846/13923730.2014.945953.
- [60] Gurevitch, J. *et al*, “Meta-analysis and the science of research synthesis”, *Nature Publishing Group*, vol. 555(7695), pp. 175–182, Mar. 2018, doi: 10.1038/nature25753.
- [61] Wang, X. *et al*, “IoT-Based Intelligent Construction System for Prefabricated Buildings: Study of Operating Mechanism and Implementation in China”, *Applied Sciences*, vol. 10(18), p. 6311, Sep. 2020, doi: 10.3390/app10186311.
- [62] Cao, X. *et al*, “A comparative study of environmental performance between prefabricated and traditional residential buildings in China”, *Journal of Cleaner Production*, vol. 109, pp. 131–143, Dec. 2015, doi: 10.1016/j.jclepro.2015.04.120.
- [63] Hong, J. *et al*, “Barriers to promoting prefabricated construction in China: A cost–benefit analysis”, *Journal of Cleaner Production*, vol. 172, pp. 649–660, Jan. 2018, doi: 10.1016/j.jclepro.2017.10.171.
- [64] Gao, Y. and Tian, X.-L, “Prefabrication policies and the performance of construction industry in China”, *Journal of Cleaner Production*, vol. 253, p. 120042, Apr. 2020, doi: 10.1016/j.jclepro.2020.120042.
- [65] Wu, H. *et al*, “Stakeholder Perceptions of Transaction Costs in Prefabricated Housing Projects in China”, *Journal of Construction Engineering and Management*, vol. 147(1), p. 04020145, Jan. 2021, doi: 10.1061/(ASCE)CO.1943-7862.0001947.
- [66] Wuni, I. Y. and Shen, G. Q, “Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong”,

Sustainable Production and Consumption, vol. 29, pp. 574–587, Jan. 2022, doi: 10.1016/j.spc.2021.11.010.

- [67] Durdyev, S. and Ismail, S, “Offsite Manufacturing in the Construction Industry for Productivity Improvement”, *Engineering Management Journal*, vol. 31(1), pp. 35–46, Sep. 2018, doi: 10.1080/10429247.2018.1522566.
- [68] Bendi, D. *et al*, “Assessing off-site readiness in construction organisations: cases from India”, *Construction Innovation*, Vol. 22, pp. 320- 341, Jul. 2021, doi: 10.1108/CI-01-2021-0005.
- [69] Navaratnam, S. *et al*, “Performance Review of Prefabricated Building Systems and Future Research in Australia”, *Buildings*, vol. 9(2), p. 38, Feb. 2019, doi: 10.3390/buildings9020038.
- [70] Steinhardt, Dale. A. and Manley, K, “Adoption of prefabricated housing—the role of country context”, *Sustainable Cities and Society*, vol. 22, pp. 126–135, Apr. 2016, doi: 10.1016/j.scs.2016.02.008.
- [71] Steinhardt, Dale A and Manley, K, “Exploring the beliefs of Australian prefabricated house builders”, *Construction Economics and Building*, vol. 16(2), pp. 27–41, Jun. 2016, doi: 10.5130/AJCEB.v16i2.4741.
- [72] Darlow, G., Rotimi, J. O. B. and Shahzad, W. M, “Automation in New Zealand’s offsite construction (OSC): a status update”, *Built Environment Project and Asset Management*, vol. 12, pp. 38- 52, Mar. 2021, doi: 10.1108/BEPAM-11-2020-0174.
- [73] Masood, R., Lim, J. B. P. and González, V. A, “Performance of the supply chains for New Zealand prefabricated house-building”, *Sustainable Cities and Society*, vol. 64, p. 102537, Jan. 2021, doi: 10.1016/j.scs.2020.102537.
- [74] Yin, X. *et al*, “Building information modelling for off-site construction: Review and future directions”, *Automation in Construction Elsevier*, vol. 101, pp. 72–91, May 2019, doi: 10.1016/j.autcon.2019.01.010.
- [75] Gong, C. *et al*, “Factors impacting BIM application in prefabricated buildings in China with DEMATEL-ISM”, *Construction Innovation*, ahead-of-print(ahead-of-print), Oct. 2021, doi: 10.1108/CI-06-2021-0115
- [76] Zhao, L., Liu, Z. and Mbachu, J, “Optimization of the Supplier Selection Process in Prefabrication Using BIM”, *Buildings*, vol. 9(10), p. 222, Oct. 2019, doi: 10.3390/buildings9100222.
- [77] Gbadamosi, A.-Q. *et al*, “Big data for Design Options Repository: Towards a DFMA approach for offsite construction”, *Automation in Construction*, vol. 120, p. 103388, Dec. 2020, doi: 10.1016/j.autcon.2020.103388.
- [78] Bakhshi, S. *et al*, “Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite

construction”, *Automation in Construction*, vol. 133, p. 104015, Jan. 2022, doi: 10.1016/j.autcon.2021.104015.

- [79] Li, X. *et al*, “Blockchain-Enabled IoT-BIM Platform for Supply Chain Management in Modular Construction”, *Journal of Construction Engineering and Management*, vol. 148(2), Feb. 2022, doi: 10.1061/(ASCE)CO.1943-7862.0002229.
- [80] Jiang, Y. *et al*, “Blockchain-enabled cyber-physical smart modular integrated construction”, *Computers in Industry*, vol. 133, p. 103553, Dec. 2021, doi: 10.1016/j.compind.2021.103553.
- [81] Li, C. Z., Shen, G. Q., *et al*, “Schedule risk modeling in prefabrication housing production”, *Journal of Cleaner Production*, vol. 153, pp. 692–706, Jun. 2017, doi: 10.1016/j.jclepro.2016.11.028.
- [82] Lee, D. and Lee, S, “Digital twin for supply chain coordination in modular construction”, *Applied Sciences (Switzerland)*, vol. 11(13), Jun. 2021, doi: 10.3390/app11135909.
- [83] Liu, Z. *et al*, “Digital Twin-Based Safety Risk Coupling of Prefabricated Building Hoisting”, *Sensors*, vol. 21(11), p. 3583, May 2021, doi: 10.3390/s21113583.
- [84] Wasim, M., Vaz Serra, P. and Ngo, T. D, “Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction – a review”, *International Journal of Construction Management*, pp. 1–9, Nov. 2020, doi: 10.1080/15623599.2020.1837720.
- [85] Bao, Z. *et al*, “Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction”, *Building Research & Information*, pp. 1–14, Aug. 2021, doi: 10.1080/09613218.2021.1966734.
- [86] Ikuma, L. H., Nahmens, I. and James, J, “Use of Safety and Lean Integrated Kaizen to Improve Performance in Modular Homebuilding”, *Journal of Construction Engineering and Management*, vol. 137(7), pp. 551–560, Jul. 2011, doi: 10.1061/(asce)co.1943-7862.0000330.
- [87] Nahmens, I. and Ikuma, L. H, “Effects of Lean Construction on Sustainability of Modular Homebuilding”, *Journal of Architectural Engineering*, vol. 18(2), pp. 155–163, Jun. 2012, doi: 10.1061/(asce)ae.1943-5568.0000054.
- [88] James, J. *et al*, “The impact of Kaizen on safety in modular home manufacturing”, *International Journal of Advanced Manufacturing Technology*, vol. 70(1–4), pp. 725–734, Sep. 2013, doi: 10.1007/s00170-013-5315-0.
- [89] Barkokebas, B. *et al*, “A BIM-lean framework for digitalisation of premanufacturing phases in offsite construction”, *Engineering, Construction and Architectural Management*, vol. 28(8), pp. 2155–2175, May 2021, doi: 10.1108/ECAM-11-2020-0986.

- [90] Lerche, J. *et al*, “Application of Last Planner System to Modular Offshore Wind Construction”, *Journal of Construction Engineering and Management*, vol. 146(11), p. 05020015, Nov. 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001922.
- [91] Si, T. *et al*, “A Dynamic Just-in-Time Component Delivery Framework for Off-Site Construction”, *Advances in Civil Engineering*, pp. 1–19, Jun. 2021, doi: 10.1155/2021/9953732.
- [92] Nolan, G, “Managing risk while translating research outcomes into design and construction innovation”, *Architectural Science Review*, vol. 61(4), pp. 255–265, Jun. 2018, doi: 10.1080/00038628.2018.1473241.
- [93] Choi, J. O., O’Connor, J. T. and Kim, T. W, “Recipes for Cost and Schedule Successes in Industrial Modular Projects: Qualitative Comparative Analysis”, *Journal of Construction Engineering and Management*, vol. 142(10), Oct. 2016, doi: 10.1061/(ASCE)CO.1943-7862.0001171.
- [94] Wuni, I. Y. and Shen, G. Q, “Exploring the critical success determinants for supply chain management in modular integrated construction projects”, *Smart and Sustainable Built Environment*, Oct. 2021, doi: 10.1108/SASBE-03-2021-0051.
- [95] Zhou, J. *et al*, “A selection model based on SWOT analysis for determining a suitable strategy of prefabrication implementation in rural areas”, *Sustainable Cities and Society*, vol. 50, p. 101715, Oct. 2019, doi: 10.1016/j.scs.2019.101715.
- [96] Charlson, J. and Dimka, N, “Design, manufacture and construct procurement model for volumetric offsite manufacturing in the UK housing sector”, *Construction Innovation*, vol. 21(4), pp. 800–817, Feb. 2021, doi: 10.1108/CI-10-2019-0108.
- [97] Hung, H.-F., Kao, H.-P. and Ku, K.-C, “Evaluation of design alternatives in collaborative development and production of modular products”, *The International Journal of Advanced Manufacturing Technology*, vol. 33(11–12), pp. 1065–1076, Apr. 2006, doi: 10.1007/s00170-006-0548-9.
- [98] Lu, W. and Yuan, H, “Investigating waste reduction potential in the upstream processes of offshore prefabrication construction”, *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 804–811, Dec. 2013, doi: 10.1016/j.rser.2013.08.048.
- [99] Xu, J. *et al*, “A four-quadrant conceptual framework for analyzing extended producer responsibility in offshore prefabrication construction”, *Journal of Cleaner Production*, vol. 282, Feb. 2021, doi: 10.1016/j.jclepro.2020.124540.
- [100] Almashaqbeh, Mohammad and El-Rayes, K, “Minimizing transportation cost of prefabricated modules in modular construction projects”, *Engineering, Construction and Architectural Management*, ahead-of-p(ahead-of-print), 2021,

doi: 10.1108/ECAM-11-2020-0969.

- [101] Almashaqbeh, M. and El-Rayes, K, “Optimizing the prefabrication finishing level in modular construction”, *Canadian Journal of Civil Engineering*, vol. 48(11), pp. 1534–1540, Nov. 2020, doi: 10.1139/cjce-2020-0346.
- [102] Hammad, A. W. *et al*, “A novel mathematical optimisation model for the scheduling of activities in modular construction factories”, *Construction Management and Economics*, vol. 38(6), pp. 534–551, Nov. 2019, doi: 10.1080/01446193.2019.1682174.
- [103] Chen, Y., Okudan, G. E. and Riley, D. R, “Decision support for construction method selection in concrete buildings: Prefabrication adoption and optimization”, *Automation in Construction*, vol. 19(6), pp. 665–675, Oct. 2010, doi: 10.1016/j.autcon.2010.02.011.
- [104] Zhao, J. and Ke, G. Y, “Optimizing Emergency Logistics for the Offsite Hazardous Waste Management”, *Journal of Systems Science and Systems Engineering*, vol. 28(6), pp. 747–765, Oct. 2019, doi: 10.1007/s11518-019-5429-5.
- [105] Hsu, P. Y., Angeloudis, P. and Aurisicchio, M, “Optimal logistics planning for modular construction using two-stage stochastic programming”, *Automation in Construction Elsevier*, vol. 94, pp. 47–61, Sep. 2017, doi: 10.1016/j.autcon.2018.05.029.
- [106] Chen, W. *et al*, “Collaborative scheduling of on-site and off-site operations in prefabrication”, *Sustainability (Switzerland)*, vol. 12(21), pp. 1–23, Nov. 2020, doi: 10.3390/su12219266.
- [107] Liu, C. *et al*, “Applications of object detection in modular construction based on a comparative evaluation of deep learning algorithms”, *Construction Innovation*, vol. 22(1), pp. 141–159, May 2021, doi: 10.1108/CI-02-2020-0017
- [108] Zaalouk, A. and Han, S, “Parameterized Design Optimization Framework for Worker-Friendly Workplaces in Modular Construction”, *Journal of Construction Engineering and Management*, vol. 147(5), p. 04021030, May 2021, doi: 10.1061/(ASCE)CO.1943-7862.0002029.
- [109] Enshassi, M. S. A. *et al*, “Integrated Risk Management Framework for Tolerance-Based Mitigation Strategy Decision Support in Modular Construction Projects”, *Journal of Management in Engineering*, vol. 35(4), Jul. 2019, doi: 10.1061/(ASCE)ME.1943-5479.0000698.
- [110] Enshassi, M. S. A. *et al*, “Probabilistic Risk Management Framework for Tolerance-Related Issues in Modularized Projects: Local and Global Perspectives”, *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, vol. 6(1), p. 04019022, Mar. 2020, doi: 10.1061/AJRUA6.0001036.

- [111] Shoval, S. and Efatmaneshnik, M, “Managing complexity of assembly with modularity: a cost and benefit analysis”, *The International Journal of Advanced Manufacturing Technology*, vol. 105(9), pp. 3815–3828, May 2019, doi: 10.1007/s00170-019-03802-2.
- [112] Shahtaheri, Y. *et al*, “Managing risk in modular construction using dimensional and geometric tolerance strategies”, *Automation in Construction*, vol. 83, pp. 303–315, Nov. 2017, doi: 10.1016/j.autcon.2017.03.011.
- [113] Li, X. *et al*, “Integrating Building Information Modeling and Prefabrication Housing Production”, *Automation in Construction*, vol. 100, pp. 46–60., Apr. 2019, doi: 10.1016/j.autcon.2018.12.024.
- [114] Golabchi, A. *et al*, “An Automated Biomechanical Simulation Approach to Ergonomic Job Analysis for Workplace Design”, *Journal of Construction Engineering and Management*, vol. 141(8), p. 04015020, Aug. 2015, doi: 10.1061/(ASCE)CO.1943-7862.0000998.
- [115] Li, Xinming *et al*, “Automated post-3D visualization ergonomic analysis system for rapid workplace design in modular construction”, *Automation in Construction Elsevier*, vol. 98, pp. 160–174, Jul. 2018, doi: 10.1016/j.autcon.2018.11.012.
- [116] Ashcroft, D. *et al*, “Cost comparison of seismic damage resisting systems for modules in multi-storey buildings”, *Journal of Engineering, Design and Technology*, vol. 17(2), pp. 330–346, Mar. 2019, doi: 10.1108/JEDT-04-2018-0076.
- [117] Chen, Z. *et al*, “Exploration of the multidirectional stability and response of prefabricated volumetric modular steel structures”, *Journal of Constructional Steel Research*, vol. 184, p. 106826, Sep. 2021, doi: 10.1016/j.jcsr.2021.106826.
- [118] Lin, T. *et al*, “Offsite construction in the Australian low-rise residential buildings application levels and procurement options”, *Engineering, Construction and Architectural Management*, ahead-of-p(ahead-of-print), 2021, doi: 10.1108/ECAM-07-2020-0583.
- [119] Akinradewo, O. *et al*, “Modular method of construction in developing countries: the underlying challenges”, *International Journal of Construction Management*, pp. 1–11, Sep. 2021, doi: 10.1080/15623599.2021.1970300.
- [120] Azhar, S., Lukkad, M. Y. and Ahmad, I, “An Investigation of Critical Factors and Constraints for Selecting Modular Construction over Conventional Stick-Built Technique”, *International Journal of Construction Education and Research*, vol. 9(3), pp. 203–225, May 2013, doi: 10.1080/15578771.2012.723115.
- [121] Vassoney, E. *et al*, “Comparing Multi-Criteria Decision-Making Methods for the Assessment of Flow Release Scenarios From Small Hydropower Plants in the Alpine Area”, *Frontiers in Environmental Science*, Apr. 2021, doi:

10.3389/fenvs.2021.635100.

- [122] Gisev, N., Bell, J.S. and Chen, T.F, “Interrater agreement and interrater reliability: key concepts, approaches, and applications”, *Research in Social and Administrative Pharmacy*, Vol. 9, pp. 330-338, Jun. 2012, doi: 10.1016/j.sapharm.2012.04.004.
- [123] Arashpour, M. *et al*, “Optimization modeling of multi-skilled resources in prefabrication: Theorizing cost analysis of process integration in off-site construction”, *Automation in Construction*, vol. 95, pp. 1–9, Nov. 2018, doi: 10.1016/j.autcon.2018.07.027.
- [124] Vithanage, S. C. *et al*, “Systematic review on the identification of safety risks in off-site manufacturing (OSM)”, *Journal of Engineering, Design and Technology*, vol. 20, pp. 935- 964, Jun. 2022, doi: 10.1108/JEDT-12-2020-0498.
- [125] Valinejadshoubi, M., Bagchi, A. and Moselhi, O, “Development of a BIM-Based Data Management System for Structural Health Monitoring with Application to Modular Buildings: Case Study”, *Journal of Computing in Civil Engineering*, vol. 33(3), May 2019, doi: 10.1061/(ASCE)CP.1943-5487.0000826.
- [126] Zhu, M. *et al*, “Two-period based carbon-economy equilibrium strategy for modular construction supply planning”, *Journal of Cleaner Production*, vol. 290, Mar. 2021, doi: 10.1016/j.jclepro.2020.125674.
- [127] Teng, Y. and Pan, W, “Estimating and minimizing embodied carbon of prefabricated high-rise residential buildings considering parameter, scenario and model uncertainties”, *Building and Environment*, vol. 180, p. 106951, Aug. 2020, doi: 10.1016/j.buildenv.2020.106951.
- [128] Alwisy, A. *et al*, “A BIM-based automation of design and drafting for manufacturing of wood panels for modular residential buildings”, *International Journal of Construction Management*, vol. 19(3), pp. 187–205, Jan 2018, doi: 10.1080/15623599.2017.1411458.
- [129] Liu, H. *et al*, “Risk management system and intelligent decision-making for prefabricated building project under deep learning modified teaching-learning-based optimization”, *PLoS ONE*, Jul. 2020, doi: 10.1371/journal.pone.0235980.
- [130] Lou, N. and Guo, J, “Study on Key Cost Drivers of Prefabricated Buildings Based on System Dynamics”, *Advances in Civil Engineering*, pp. 1–12, Oct. 2020, doi: 10.1155/2020/8896435.
- [131] Dabirian, S., Han, S. H. and Lee, J, “Stochastic-based noise exposure assessment in modular and off-site construction”, *Journal of Cleaner Production*, vol. 244, p. 118758, Jan 2020, doi: 10.1016/j.jclepro.2019.118758.

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PUBLICATIONS

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