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Construction Supply Chain Risk: Bow-Tie Analysis of Critical Material Delay

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by

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Abbreviations

AEC	Architecture Engineering Construction
BIM	Building Information Modeling
CFR	Cost and Freight
CFSI	Counterfeit, Fraudulent, and Suspect Items
CI	Construction Industry
CON	Construction Department
CSC	Construction Supply Chain
CSCRM	Construction Supply Chain Risk Management
DAP	Delivery at Place
ENG	Engineering Department
EPC	Engineering Procurement Construction
ESG	Environmental Social Governance
EPCC	Engineering Procurement Construction Contractor
ETA	Event Tree Analysis
EXW	Ex-Works
FAT	Factory Acceptance Test
FCA	Free to Carrier
FTA	Fault Tree Analysis
GCC	Gulf Cooperation Council
GIS	Geographical Information Systems
HSQE	Health, Safety, Quality, Environment
ICT	Information Communication Technology
IT	Information Technology
LR	Literature Review
O&G	Oil and Gas
PM	Project Management
PO	Purchase Order
PRC	Procurement Department
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QA	Quality Assurance
QLT	Quality Department
RE	Risk Enabler
SAT	Site Acceptance Test
SC	Supply Chain
SCADA	Supervisory Control and Data Acquisition System
SCM	Supply Chain Management
SCMS	Substation Control and Monitoring Systems

1. Executive Summary

Calculating the risk has essentially no value if there is no decision to be made and the supportive tool for that is a risk analysis which can set the stage for optimal, or at least most accurate, equilibrium between payoffs and losses. Supply Chains (SCs) struggle with risks related to the delivery of the required materials and information to the right places, at the right time, with the suitable quality. The construction industry, although it differs from the manufacturing industry in terms of its project-based nature, has to deal with some risks common to all SCs, but also with some others that are specifically present to construction projects. In this context, we conducted a semi-systematic literature review (LR) to investigate on the extant theory of the construction supply chain (CSC) risks. The LR, among others, has covered the effects of the delay of generic materials at the construction site however, the causes and the consequences of the delay of critical long-lead items to the project and by extension to the construction company as an organization have been disregarded. The link for those interfaces is the CSC hence, these risks appertain to it and thus, they should be investigated under the research topic of CSC.

For this investigation, a qualitative research for a single-case study was conducted by utilizing semi-structured interviews with CSC professionals of an Engineering-Procurement-Construction contractor (EPCC). The data gathered helped in producing a Bow-Tie model which depicts how the delay of the critical long-lead item is caused and what are its consequences. This is supported by a Fault Tree Analysis (FTA) and an Event Tree Analysis (ETA). The analysis identified 6 causal categories namely Management, Planning, Logistics, Manufacturing, Post-delivery and Force Majeure and 4 consequential categories namely Financial Damage, Legal Issues, Commercial Implications, and Decay of people. According to the risk level of each of the above-mentioned causes and consequences, measures of different urgency were identified and proposed.

2. Introduction

Risk theory

Risk is usually connected with words that express the results of hazardous events that could potentially lead to catastrophic outcomes. Theories around this topic might provide lots of explanations to facilitate the study of various disciplines. However, among various studies there is a consensus on one particular subject, which is the differentiation of reality and possibility [1]. There are events that are expected to happen because there is historical data proving their existence, and there are events that it is considered possible for them to occur but it is unsure if they even exist. The former concept is described as “risk” while the latter as “uncertainty”[2]. Simply put, a risky decision comes together with the knowledge of all potential outcomes and possibilities while on the other hand an uncertain decision is followed only by doubt of the magnitude and the odds of the effects of an event. Based on that, risk can be considered as a quantifiable term due to its possibilistic and probabilistic character [3]. The most accurate definition of the term is the one given below by John Adams in 1995 [4] which has been based on the Royal Society’s definition in 1983 [5]:

“*Risk, according to the definitions most commonly found in the safety literature, is the probability of an adverse future event multiplied by its magnitude*”

Risk can be perceived objectively and subjectively depending on the level of knowledge of the variables mentioned in the definition above [6]. For the sake of our research, we will focus on the “objective risk” (from now onwards we will refer to that as “risk” and define the rest of the cases as “uncertainties”.

Risk is quantifiable and can be measured with the use of mathematical practices [1] and this is applicable only when we address the future. Historical data is essential for the evaluation of future decisions although it cannot be solely reviewed in the context of risk expression as the environment in which these past events occurred might have changed. Calculating the risk has essentially no value if there is no decision to be made and the supportive tool for that is a risk analysis which can set the stage for optimal, or at least most accurate, equilibrium between payoffs and losses [7].

To identify the roots of adverse events and their effects, to establish redundancy measures and to determine whether or not a system is capable of withstanding risks are the basis of risk analysis [7], [8]. How precise can a risk analysis be is proportional to the level of detail of the available information at the time this takes place [7]. Despite that risk analysis can be carried out during different stages of a system or a project, in early stages like the tendering phase of a construction project for example, access to key information is limited in contrast to the operational phase thus, no apparent constraints deter a decision-maker from picking a solution out of a plentiful decision catalogue [7].

Risk evaluation may or may not be considered as a part of a risk analysis. This statement lies on the fact that risk evaluation is the appraisal process of a system's tolerability. It is one of the basic characteristics of a risk analysis although, by factoring risk acceptance criteria in a methodic way, it can be used as a standalone strategic process upon the completion of the risk analysis [8].These two processes namely, risk analysis and risk evaluation, comprise the risk assessment process. The act of taking risk-reducing measures and estimating their effectiveness subsequently to risk assessment is part of the risk control process. All three processes constitute the risk management process [9] as in Figure 1 Risk Management Process.

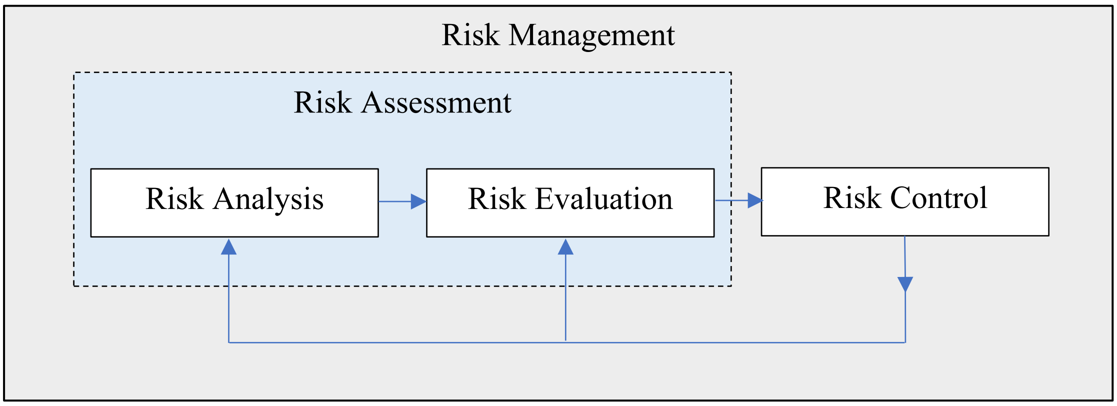

Figure 1 Risk Management Process

As summarized in ISO 31000:2018(E) guidelines for risk management, successful implementation of the framework requires the engagement and awareness of stakeholders [10]. This enables organizations to explicitly address uncertainty in decision-making, while also ensuring that any new or subsequent uncertainty can be taken into account as it arises. Properly designed and implemented, the risk management framework will ensure firstly that the risk management process is a part of all activities throughout the organization, including decision-making, and secondly that changes in external and internal contexts will be adequately captured [10]. This interpretation explains why risk management is not a self-contained one-shot process but rather a continuous one that demands the appropriate constant attention by those who are liable of sustaining a system's integrity.

<u>What We Research</u>

The purpose of this thesis is to support stakeholders of the CSC by reviewing the literature that is related to the construction supply chain risks, to depict the research themes, and to identify the research gaps. The construction industry (CI), despite standing on firm foundations, lacks the level of innovation of other traditional industries. Demanding clients will only collaborate with contractors that meet the highest quality standards, a situation that pushes the development boundaries of the CI further and further. Although, traditional as the CI is, there has been detected that construction organizations struggle to adopt new management methods and technologies. This can also be proved by the digitalization booming that COVID-19 caused. This thesis will increase the understanding of risk of the readers by exploring the CSC process design and will help to understand if the measures that have been taken reduce the risk to acceptable levels.

Conclusively, the CI, in the context of the CSC, has grasped the need of being innovative but the unexpected rise of quality demand by the market has not given it enough room to hatch naturally. This thesis will bridge the gap between the old and the new construction supply chain risk management (CSCRM) mentality.

The fulfillment of the purpose of this thesis will shed light to the following questions:

- What relevant literature can be found when investigating risk in the construction supply chain context?
- What themes are addressed in the literature on construction supply chain risk?
- What research gaps are identified in the literature on construction supply chain risk?

Research Gap and Research Question

The relevant literature has extensively covered the CSC associated risks in the context of management, collaboration and relationships, technology, and visibility in different geographical areas, for various construction methods and processes and for different organizational types and sizes. The relevant literature though has not managed to gather and categorize the causes and the consequences of the delay of materials that are on the critical path of the project management (PM) schedule and have long lead time. This thesis will try to delve into the route of the CSC in order to investigate the different nodes the lead to this major project risk and will aim at presenting the barriers that need to be placed prior to the critical event (delay) so that to avoid it from happening and after that critical event so that to mitigate its repercussions. Subsequently, the research question that is formed by the aim of this thesis is:

What are the causes and the consequences by the delay of equipment or material that are on the critical path of a project management schedule and have long lead time?

Expected findings

The results of that research are expected to shed light on the project risk awareness by investigating on the effective barriers that could prevent a major project risk from happening and the measures that could prevent the expansion of the problems that such event can give rise. This thesis will provide a risk map of critical path materials to the professionals of the construction industry and will ultimately try to evolve the CSCRM process by presenting the true complexity of the CSC flow. The analytical way of presenting the threats, the barriers and the consequences of a critical event in the CSC constitutes an evolution of the CSC. Besides the construction professionals, other disciplines might be benefit from the findings such as those that design IT software like (Building Information Modeling) BIM or PM platforms and professionals of the Quality Assurance industry.

Structure

To support the above goal, we will first refer to the peculiarities of the CI and its SC and will provide the most scientifically acceptable definitions of the terms SC, Supply Chain Management (SCM), and SCRM. The aforementioned will comprise the Section 1 of this thesis and will help to provide the basics for understanding in more depth the Theoretical Background in Section 2. Afterwards, in the Section 2 of this thesis we will provide the Theoretical Background of the CSC risks with the aim to gather how the literature has investigated this theme and what are its findings. This Section will also highlight what are the topics of CSC risks under investigation and what aspects have not been addressed in this context.

3. Section 1

Supply Chains

Supply chains (SCs) enable the movement of both physical and non-physical resources between businesses. To meet escalating customer expectations and safeguard their competitive edge, SCs must proactively anticipate and address potential disruptions [11][12]. Additionally, they face the challenge of making decisions that support a more sustainable future, all while navigating an increasingly volatile, uncertain, and error-intolerant business landscape. This dynamic environment underscores the substantial growth of global trade, which has significantly influenced supply chains, particularly in terms of risk management.

SCM deals with issues of that nature from the operational up to the strategic level. As we are entering the era of SC competition, the span of risk that may arise in the way of a SC's activities can derive from direct and non-direct links, making it a complex system to organize and plan in, with sometimes impossible to foresee events unfolding. A successful SCM embraces and embeds risk in a systematic process that aims to attach further value to business' efficiency.

Supply Chain Risk Management (SCRM) Theory

Risk in SCs produces adverse effects but these are expected by the decision-makers. What distinguishes the good from the vague and insufficient SCM practices is resiliency [11]. The ability to be resilient to that risk is not the power to avoid being influenced negatively, but the power to recover fast and become stronger. Unforeseen events strike SCs on a regular basis and can drive major players off the market race if they avoid incorporating SC risks into their overall risk assessment processes.

Resiliency differs from efficiency whose focus is on improving the economic functionalities [13]. Unawareness of efficiency factors and poor management can cause conflicts with resiliency management and ultimately expose a firm to disruptive risks. Cost cutting is often misinterpreted with cost efficiency strategies such us outsourcing non-core activities although this turns firms susceptible to the risks posed to their suppliers [14].

Modern SCRM strategies require decision-makers to avoid obsolete handbooks and guidelines that praise a risk aversion culture that eventually withhold businesses from catching up with the ever-growing markets and instead being more aggressive in an adaptive framework. This is highlighted by the study [15] where the authors categorized the SC risk mitigation approached into two categories namely redundancy and flexibility. In this context, the following definition encapsulates the meaning of SC resilience.

"the adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost-effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior of the disruption"[16]

In conventional organizations' management structures, the end-to-end risk management is subverted by the "bordering" of responsibilities between the different departments of an organization. This management culture does not allow the organization to methodologically explore how and adverse effect in a SC may produce issues on another business aspect of a company as for example on the Finance department. SCM seeks to provide an overall coordination and cooperation of functions like sourcing, manufacturing and marketing considering risk as a general threat to the whole business activity.

SCs are complex systems, which are prone to risks and uncertainty. In the context of a SC, this aligns with the general idea that risk is about triggering events that either affect a single focal firm or the performance of a SC as a network [12], [17], [18], [19], [20]. In order to visualize the extent of risk exposure of a SC, we firstly need to provide some contextual definitions in regard to the latter. Martin Christopher defines a SC as:

"*the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer*" [21]

SCM is defined by Mentzer, Dewitt, Keebler, Min, Nix, Smith, and Zacharia as:

"*the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole*"[22]

SC risk is therefore a challenge posed to all the nodes of such networks that seek not only to improve in terms of efficiency as part of a chain, but at the same time to be even more effective as units in order to gain rewards out of the system's overall performance.

The definitions of SC risk provided are often ambiguous and are unable to establish a consensus around the quantification of this concept hence, SCRM is a rather arbitrary concept. In their common thesis, Heckman, Comes and Nickel, after reviewing and analyzing the concept of SC risk, proposed the following definition [23].

"*Supply chain risk is the potential loss for a supply chain in terms of its target values of efficiency and effectiveness evoked by uncertain developments of supply chain characteristics whose changes were caused by the occurrence of triggering-events*"

By the etymology, an adverse future event is unforeseen and uncontrollable especially if such has never happened (it is uncertain) or been recorded thus, it is impossible to plan for suppression strategies even by using sophisticated simulation models that their output is derived by the analysis of historical data [24]. The primary consideration towards setting the foundation for proper SCRM is identical to that of every discipline's risk management methods and that is by isolating four fundamental constructs. These are the SC risk sources, SC risk consequences, SC risk drivers and the SC risk mitigation strategies [20]. In an in-depth analysis on the sources of SC disruptions, Stecke and Kumar distinguish the catastrophes in natural and man-made (intentional and unintentional), and they further elaborate on the four SC "vulnerability causing factors" namely, the increase in the number of exposure points, the increase in distance/time, the decrease in flexibility and the decrease in redundancy [25]. Their research contributes to the formation of a basic methodology to support the preparation of mitigation strategies against catastrophes.

In today's markets, operational and financial implications caused by SC interruptions pose the biggest problem to firms [26] although risk and disruption, despite being closely related, can exist separately because risks cause disruptions but sometimes disruptions are avoided [19]. Is it still unknown why the majority of organizations do not take appropriate action to avoid these implications while they are aware of their results, but it is clear that the former have insufficient knowledge on the occurring possibilities of those events and therefore do not perform any economic analysis to endorse more robust contingency plans [27].

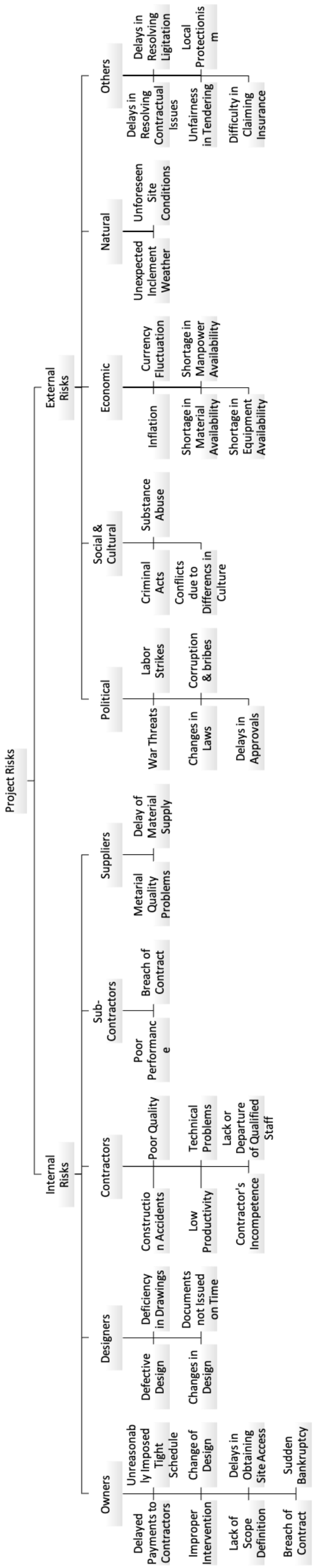

Figure 2 The Construction Project Risks [28]

4. Section 2

<u>Theoretical Background</u>

Given the defined scope of this research, a comprehensive systematic literature review is beyond the scope of this study. However, to establish a robust theoretical foundation and contextualize the present study within existing scholarship, a semi-systematic literature review methodology has been adopted. This approach, while not exhaustive, adheres to the principles of systematic review processes, incorporating elements of the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines to ensure transparency and rigor in the literature search and selection process PRISMA protocol is adopted to offer the replicability of the study [29] and the review stages are structured according to the methodology proposed by Tranfield D et al. [30]. These stages are (a) planning for developing the research aim, question, and search criteria; (b) conducting the review; and (c) reporting and dissemination stage.

The review utilized the keywords (supply chain*, risk*, construction industry) with the aim of researching the self-explanatory subjects and their relevance. The literature was found through two of the most prominent data bases Scopus and Web of Science. More specifically, the Boolean logic was used, and the keywords were typed as ("supply chain*" AND risk* AND "construction industry") as in *Table 1* Literature Review Search Strings. The reason behind choosing to keep the words "supply" and "chain", as well as the words "construction" and "industry" together, was to look up for literature related to the supply chain(s) of the construction industry and avoid filtering in irrelevant topics. The initial sample of documents was 287 through Scopus and 146 through Web of Science. The filters that shaped the inclusion and exclusion criteria that were applied in Scopus were the document type (limited to articles, reviews and conference papers), the publication stage (limited to final), the source type (limited to journals) and the language (limited to English) with no time boundaries placed while for Web of Science the filters that were used were the document type (limited to articles and reviews) and the language (limited to English), while no time boundaries were set as in *Table 2* Inclusion and Exclusion Criteria of Search Protocol. The database search had been conducted on May 2024.

Keywords	Boolean Search Operator	Content Searched	Searched Strings
Supply Chain Supply Chains Risk Risks Construction Industry	AND	Title or Keywords or Abstracts	"Supply Chain*" AND "Risk*" AND "Construction Industry"

Table 1 Literature Review Search Strings

Inclusion and Exclusion Criteria			
Primary Data		Secondary Data	
Inclusionary	Exclusionary	Inclusionary	Exclusionary
Journal Articles, Review, Conference Papers	Other Document Types	CSC Risks and Uncertainties	Not Related to the Construction Industry
Source Type Journals	Other Source Type	CSCRM	Not Related to CSC
Final Publication Stage	Other Publication Stages	Relevant to the Research Objectives	Not Related to Risks
Language English	Other Languages		Other Irrelevant Subjects
All Time Range			

Table 2 Inclusion and Exclusion Criteria of Search Protocol

The quantity of documents that were excluded after applying the filters was 124. The number of duplicate papers was 96. The abstracts of these articles were read to filter out those that were not aligning with the topic of interest. The selection criteria that were used are shown in *Table 3* Selection Criteria. After this process a total of 81 articles were held and tabulated in *Appendix 1*. The process for literature screening and selection can be seen in *Figure 3* PRISMA Selection Process.

Selection Criteria
Identify the Internal Risks of the CSC
Identify the External Risks of the CSC
Identify other Elements that Affect the CSC

Table 3 Selection Criteria

A sum of 132 articles of the second stage records were excluded due to their non-conformity with our specific topic. While in the first view most of the excluded articles seemed to be related to the context of this thesis, after completing a thorough review of them it was decided that the findings of those could not contribute to the research aim. The theme of risk for example was present to the whole excluded literature but in the context for example of project cost variations [31], process-waste reduction [32], credit risk assessment [33], slavery risk [34], health risks [35] and others where there was either no or minimal reference to the CSC, it was determined those needed to be excluded. Other themes that were totally excluded were engineering, government, HSQE, social, and themes related to other industries.

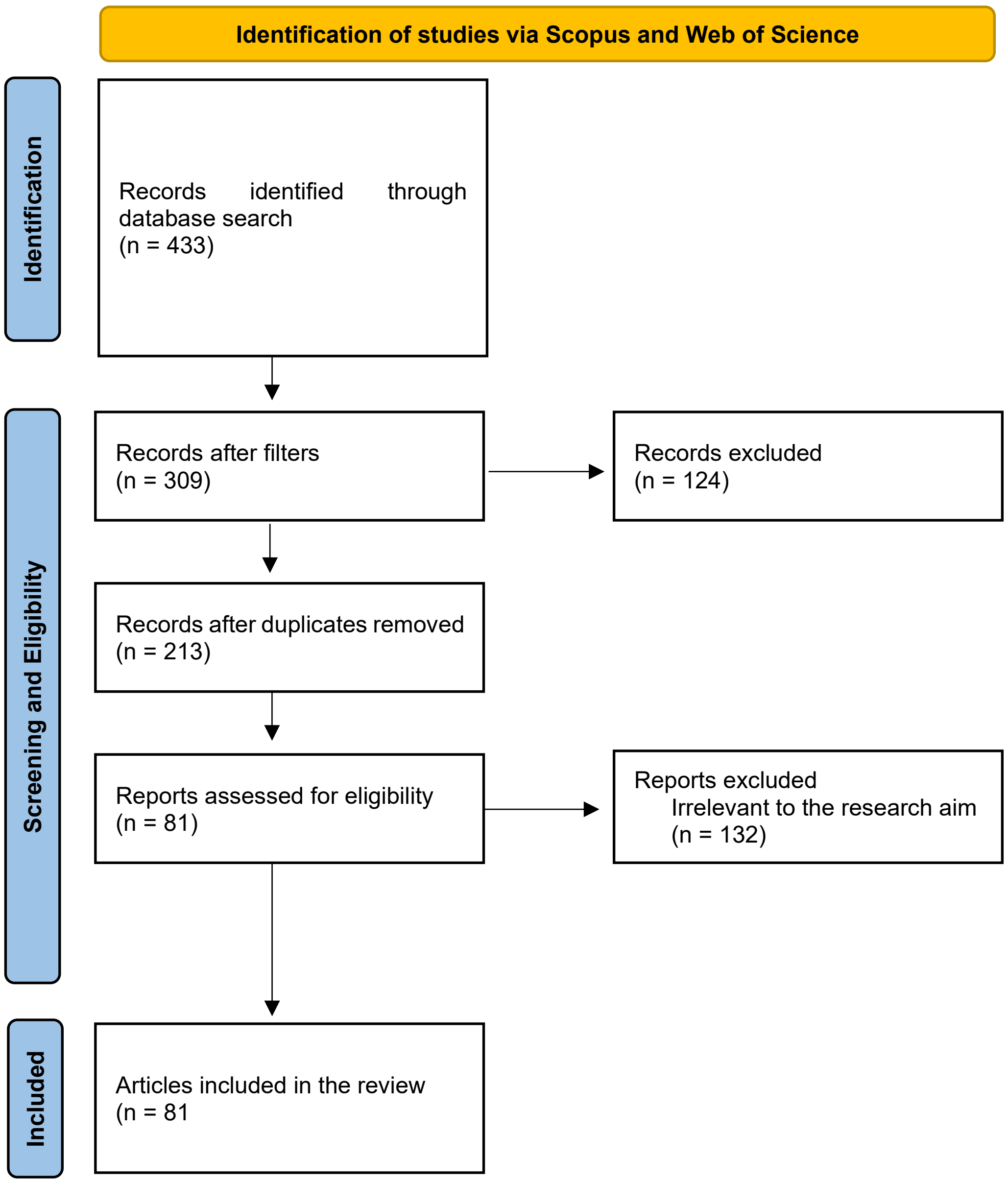

Figure 3 PRISMA Selection Process

At the last stage, a qualitative analysis for the final sample was performed in order to answer the following questions:

1. What are the themes addressed to these articles?
2. What research gaps were identified?

After analyzing the topics of the included articles, 9 themes were identified namely: risk, management, tools, collaboration, impact, resilience, visibility, sustainability and vulnerability. Some of the articles were discussing 2 or 3 of these themes in parallel while some others where just focusing on a specific one. The themes are presented in *Table 4* Themes of the Literature and their Count. The first column (Themes) includes the 9 the specific themes which can be found between the asterisks (*) while the combined themes are below them. In the second column (Count) there is the quantity of papers which are related to the corresponding theme or the combined themes. Lastly, the third column (Percentage) depicts the percentage of the theme's presence in the total literature.

Some of the articles that were excluded from the final list were also related to these 9 topics although the research objective and subsequently the outcome of them would not contribute to the aim of this thesis. Other themes that were not aligned with the aim were related to commercial, engineering, finance, government, sustainability, health-safety-environmental, social and other industry.

Theme	Count	Percentage
risk	21	25,93%
management	9	11,11%
risk, management	8	9,88%
tool	7	8,64%
management, collaboration	7	8,64%
risk, tool	6	7,41%
tool, management	4	4,94%
risk, management, collaboration	3	3,70%
impact	2	2,47%
risk, impact	2	2,47%
tool, visibility	2	2,47%

risk, collaboration	1	1,23%
risk, resilience	1	1,23%
tool, sustainability	1	1,23%
resilience	1	1,23%
impact, resilience	1	1,23%
visibility	1	1,23%
vulnerability	1	1,23%
impact, sustainability	1	1,23%
collaboration	1	1,23%
management, visibility	1	1,23%

Table 4 Themes of the Literature and their Count

From the analysis above it is visible that most articles around construction supply chain risk management were related to risk identification (25,93%). Second most researched subject was risk management (11.11%), and lastly, the most researched combined theme was risk and its association with managerial elements like culture (9,88%). Other topics were also found but with less or minor correlation with our theme.

The literature in the context of risk touches three main topic groups namely "Organizations" which includes CSC participants and their relationships/behaviors, "Management" which covers the material management, the risk management, the green management, and lastly "Technology" that studies the involvement of software like BIM, technologies like blockchain and other systems in the CSC [36]. A sample of 42 articles based in the PRISMA protocol criteria address or involve the theme of risk in the context of CSC.

CSC Risk

Many studies aimed at identifying the critical risk factors of a construction project. SC operations seem to have the strongest direct effect on the project performance [37]. Construction organizations are more prone to budget overruns, poor information coordination, insufficient management oversight, and error visibility to stakeholders [38]. Construction projects bring together dissimilar but contractually bound parties like owners, designers, contractors, sub-contractors, suppliers, manufacturers, and others. All these parties have different interests, objectives and functions yet they share the same goal which is the project completion [39].

All these parties share almost every aspect of risk. One study ranked those according to their impact, and found that those are funding, shortage of material/equipment, cash flow, bad weather, ISO certification and prefabricated construction (PC) preparation [40]. Another study which collected data by professionals of large-scale construction companies who were asked about the reasons of supply delays concludes that miscommunication between the company and the vendor results is the most usual reason followed by payment delays while the same study continues by stating that secondary risk factor such as hurried purchases and inadequate storage lead to order variations which eventually affect the completion time [41]. Some of these findings were in line with another survey that investigated the underlying causes of delays in the Portuguese construction industry. It revealed that slow decision-making, changes to orders, unrealistic time schedules and specifications in contracts, financial constraints on the part of the contractor, improper planning, poor consultant performance, inefficient site management, owner's influence, bureaucracy, and sub-standard contracts are the main reasons of delays [42]. In general, technical and environmental risks do not affect construction project success but management risk and financial risk do [43].

Moreover, the need to identify risks prior to the construction phase of a project can avoid great project delays as a study focusing on the counterfeit, fraudulent, and suspect items (CFSI) suggest [44]. Based on that, several articles underline the need for proactive risk management like considering local SC conditions during the design phase [45] and the study of risk enablers (REs) and the role of assessing their impact prior to the construction phase [46].

Besides the supply side risks which involve any unplanned activity with negative effect in the upstream flow of the CSC, there is also the demand side risks which involve activities that affect the CSC in the same way in the downstream flow. Such occurrences are usually towards the end user, who in this context is the client, and are related with wrong order placements or changes in the orders of materials and equipment [47]. Another study that focuses on project complexity and risk management confirmed that risk management processes in CI examines risks individually and not in parallel and that decision-makers rely solely on their intuition and past experience. Despite being aware of project complexity, not all of its aspects are included within the risk analysis [48]. Complexity is also present in project interfaces which are the interaction nodes between the stakeholders. Interface risk is a major challenge for the CI as it is involved in all phases of such projects [49]. According to a review on CSC risk management, the common assumption is that risk avoidance is through outsourcing and sub-contracting which by itself produces delays that are in line with the interface risks [50], [51]. An article about the elimination of interface risk in the CI recognized two types of interest conflicts namely "interface events" and "interface tasks" in order to set the foundation for mitigating interface risks [52].

CSCRM

CSCM is a concept that its integration has been studied for almost every type of construction methodology [53]. Business performance of a construction organization is as important as the performance of its projects and these two aspects are interlinked [54]. There are several factors that affect the performance of a project such as the level of technical and engineering expertise, the selection of committed partners, management expertise, the creation and the continuance of good working environment, the appropriate risk management, the protection of a reliable international materials supply chain, and the efficient project planning and tracking system but, especially in international projects, management expertise is the most important. This fact lies in the ability of top management to solve issues during their course without having to rely on bureaucratic, time-consuming processes [55]. CSCRM therefore is the process of defining the CSC risk sources, CSC risk consequences, CSC risk drivers and the CSC risk mitigation strategies.

A plethora of studies aimed at investigating the CSCRM in different ways such as providing decision-making models for prioritization of critical supplies [56], considering alternative risk management strategies by using different perceptions such as neo-institutionalism [57], producing new concepts on the relationship of risk and SC performance [58] and by focusing on small-scale, local, easier to study industries such the road construction of Sri Lanka [59], other but fully related SCs like the service-oriented SCs and the risks they face [60].

CSCRM follows the process path of a generic SCRM, a topic that is well studied although, not all SCM concepts of the manufacturing sector may not find applicability in the construction industry [52]. The contractor has the main responsibility of the project risk management and clients take that variable into great consideration upon deciding who will undertake a project [61].

Despite organizations’ attempts to adopt risk management strategies to protect their vulnerable points they usually fail to do so simply because it is impossible to be prepared for all potential risks. The concept of industrialized construction, which involves the implementation of innovative technologies and methods to the construction industry, has the potential of reducing these vulnerabilities by the reinforcement of CSC capabilities such as flexibility, visibility, adaptability and others [62]. Following the same path, another study revealed the most effective risk capabilities are visibility of people, products, and assets, collaborative information exchange, business intelligence gatherings, alternative suppliers, and inventory management systems [38]. Although, industrialized construction is a fairly new concept and has not been tested in complex projects thus no safe outcome can be derived in regard to its usefulness [63]. Furthermore, the concept of SC innovation (SCI) has been connected with SCRM by a study that focuses on the potential competitive advantages of such implementation in the buyer-supplier relations [64]. The impact of the same relationship on the CSC is further examined by another study which suggests that a high-quality buyer-supplier relationship gives the buyer better decision leverage by handling such transaction on his own rather than involving third party financial instruments [65].

Risk management strategies have made some progress regarding the viewpoint of risks. Outsourcing activities has been proved to be a good strategy for risk management but responsibilities cannot be outsourced hence, construction companies need to be actively involved in risk management during the whole project [66]. Moreover, another study suggests that decision-makers should shift from managing risk towards managing uncertainties which do not just take into consideration the risk assessment and the risk control of individual threats but also consider the opportunities arising within a network setting [67].

SC practitioners dealing with recurrent troubles become more experienced in handling such events but the bigger challenge in to manage unpredictable threats [68]. Huge SC disruptions that occurred lately such as the COVID-19 pandemic have resulted in the deeper understanding of the SC risks. Results of a study that investigated the common factors that affected construction project objectives showed that contract suspension, contractor bankruptcy, materials prices escalation, contract claims, inappropriate risk allocation, non-compliance with social distancing guidelines, skill shortage and poor site and virtual communication were the major project performance causes [69]. Such disruptions increase the complexity of a CSC and therefore make it more vulnerable. Globalization is another variable adding to this complexity and introduces more SC risks which are somehow identical to those introduced by the COVID-19 disruption [70]. Based on the above, the different nodes of a CSC have to deal with the same amount of complexity since the CSC is not different from the rest in the context of trade. Another study investigated the concurrent occurrence of SC disruptions by focusing on Brexit and the COVID-19 effects in the British CI. This study indicates an overall impact on material cost increase, CSC interaction, and logistic and haulage delay [71].

Successful SCM requires the integration of IT infrastructure, organizational coordination, risk management processes, and proper understanding of supply chain resilience and complexity [72]. Tries to quantify the effects of SCM on a construction project performance have found that its improper handling is likely to produce significant project disruptions [73]. Furthermore, re-engineering of CSCM has been discussed more and more based on the ever-increasing customer demands [74] and the need for a systematic approach rather than single-objective optimization is lately under the microscope of the academia research on CSCRM [75]. This idea has been investigated in the context of construction logistics management process which is mainly coordinated by merchants collaborating with the contractors. The results of this study highlighted that demand variability from the contractor's side causes major issues in the CSC and results in increased complexity [76].

Quality assurance (QA) seems to be in the forefront of the managerial practices, within CSCRM, that were reevaluated. Four main aspects of QA need to be considered as ignorance about them results in poor preparation. These are people, process, policy and technology [77]. The need to have the appropriate people assigned to risk management activities has been observed in the literature [78]. The authors of another study focusing on the performance measurement of construction suppliers in the context of localization, agility and digitalization highlight the need of the construction companies to assess, among other, suppliers' ability in SC automation stating that: *"From now on* (meaning the post-COVID era)*, we will witness a wide range of disruptive transformations and various megatrends overshadowing the construction*" [79]. Some construction organizations have already identified these parameters and are aware of their criticality. It is known to the industry that contractors usually strategically transfer their risk to the sub-contractors increasing in a way the latter's costs and decreasing the levels of trust and reliability among them ultimately undermining project efficiency [80]. The literature has covered the potential advantages of the utilization of systems like BIM in risk management [81] although crucial obstacles need to be overridden in order to successfully implement innovative solutions [82].

Disruptions of SCs have given rise to another fundamental concept which is resiliency. Poor resiliency in the CI is caused by low digitalization, imported material and machineries, labor-intensive methods and lack of experience in virtual team management, complex cash flows, diverse stakeholders and dependencies on foreign expertise [83], [84]. COVID-19 brought construction firms in confront with major SC disruptions but these eventually gave valuable lessons towards a resilient CSC [85]. Among the changes the COVID-19 brought to the CI, the process of supplier assessment was one of the major ones since major SC delays are supply-sided. A number of resilient criteria such as management support, supplier experience and reputation, economic stability, environment conservation, vulnerability to risk, collaboration in risk reduction, and supplier sustainability and training have been suggested by practitioners who intended to resolve the supplier selection problem under complex conditions and in the absence of appropriate supplier information [86].

<u>Collaborations and Relationships in CSCM</u>

Poor CSC relationships lead to poor project performance. The lack of good CSC relationships produces time delays, cost overruns and quality defects [87] while collaboration approaches such as information sharing, contractual governance and joint decision making bring positive CSC performance outcomes [88], [89]. Another research found that partnerships have important impact on the CSC performance [90]. A systematic literature review aiming at identifying the relational forms adopted by the construction companies found that the following were the ones mostly reviewed by the scientific community. These are partnering, alliancing, project delivery methods, supply chain integration, joint ventures, integrated project delivery, joint risk management, collaborative design, contingent collaboration, quasi-fixed network, resource sharing, and collaborative planning, which were interrelated with elements that affect them such as drivers, barriers, facilitators and outcomes [91].

In line with the significance of the supplier assessment is the topic of the contractor assessment and selection. Clients and contractors in the CI usually see each other as an opposing party, culture that produces drawbacks of adversarial nature like improper risk sharing tactics [92]. In the context of risk in the CSC, the former can give rise to opportunistic behaviors in a client-contractor or contractor-subcontractor relationships which subsequently affects project performance [93].

The management of CSC relationships is problematic due to the project-based nature of the CI. Contrary to the manufacturing industry that utilizes the same SC for several years in a row, the CSC seems to be unable to do so due to the lack of continuous exchanges between the construction organizations and their suppliers [89], [94], [95]. Although, a study that aimed specifically in identifying the factors that affect a project-based SC relationship environment found that integrity, respect and fairness, prompt payment and willingness to negotiating risk and price are the key elements to be considered, result that could be expected if the industry under examination was the one of manufacturing [96]. The same study concludes that trust is by far the most key factor shaping the relationship of a contractor with a sub-contractor.

Technology in CSCM

The CI has the notion to integrate innovative technologies and methods. The use of Information Technology (IT) systems for modeling of risk in the construction company is not a new trend [97], [98], [99], but the use of certain innovative technologies such as blockchain is still in its infancy [100]. The sentiment of valuable improvement to the CSC by the utilization of new technologies is present to the construction industry employees [101]. Human engagement in the process of digitalization of CSC has a crucial role for its success [102]. The use of IT systems like BIM and Geographical Information Systems (GIS) models have been studied in parallel to spatially analyze the logistical capabilities of suppliers during the selection process in order to assess their resiliency [103]. Mobile apps can provide live data for equipment tracking [104], modeling systems can accurately predict logistical variables [105], and big data management systems can support real-time responds to SC problems [106]. Furthermore, the novel blockchain technology, when properly implemented in to the

CSC, can improve the trust, transparency, traceability and efficiency [107], [108], while the artificial intelligence can be engaged in strengthening the risk management by analyzing textual data from news reports and support decision-making [109].

The implementation of transaction technologies and intelligent tools has yet to reach the appropriate maturity stage. Despite the promising findings acquired by their use certain implementation barriers such as lack of trust in the technologies, unclear advantages, security, privacy, interoperability, collaboration, education, culture, opportunism and others will have to be clarified and overcome [101], [107], [108], [110], [111]. BIM technology despite having positive impact on operational applications it cannot provide any significant advantages for strategic business trends like organizational flexibility and integration of new concepts [112]. Financial risk in the construction industry has been ascertained as one of the main SC risks but there has been no information communication technology (ICT) that could directly overcome those [113]. A study on the Australian CI found that BIM can improve the information asymmetry between the interfaces of a project but highlighted that, in order for this to be applicable, the relationship between the head contractor with the other parties will firstly have to reach a certain level of maturity since, as empirical findings suggest, the party that sets up the BIM automatically gains a power leverage over his counter-parties [110]. The implications of utilizing smart technologies for CSCM have also been mentioned in another study that investigated the success factors of hybrid-intelligent systems for the mapping of precast concrete SCs. The results shown that the poor coordination and communication derived from human interfaces negatively affect the system's artificial nodes yielding system failures [114].

Visibility in CSC

Proper decision-making in construction projects requires a complete and firm risk management process that considers visibility as one of the main elements of information input. CSC decisions are taken during the phases of design, procurement and construction since the identification of materials/equipment required, their lead time is key CSC decision area since suppliers are the major source of CSC vulnerability [115]. An investigation on the different perceptions of the CSC parties found that, in general, visibility in the industrial construction projects is low [116].

It is evidenced by the literature that, in the context of CSCRM, the variety of research themes is large and adequate. The topic of CSC risk has been studied from different perspectives stretching from the operational till the strategic management of a construction organization. Furthermore, the subject topic has been also researched for different construction business activities such as those of an EPC and architecture-engineering-construction (AEC) contractor, for civil, industrial and O&G projects, and from the perspectives of each CSC stakeholder like the one of the head-contractor, the one of the sub-contractor and the client's. All those have been studied for different geographical locations, for developed or developing countries, in periods prior, during and after major SC disruptions such as the one of COVID-19.

What emerges by literature that was studied in order to fulfill this thesis' aim was that many of those papers have suggested that CSC performance, similarly to regular SCs, affect business performance. In this context, extant literature suggests that it is crucial for proper CSCRM to consider the whole system's performance in the process. The literature has offered valuable insights on the collaboration of the CSC affiliates, the management of the SC interfaces and the potential benefits of innovative tools for its performance for the inner and the outer environment of a construction company, for both supply and demand-sided flows. Although, there is mere evidence about the perception of CSC risk of the CI organizations in whole. In other words, the literature has gained insights from professionals that are directly involved in the CSC operations (project managers, SC managers, logistics managers, consultants, top management, sub-contractors, suppliers, etc.) and has omitted to ask the CSC risk perception of the professionals that work in a construction company but are not directly involved in the CSC (Finance managers, Quality managers, Business Development Managers, etc.). The need to investigate the perceptions of the professionals who work for functions that are indirectly involved in the CSC lies on the idea that firstly, project performance is an organizational goal and not a goal of just two or three business functions, and secondly in order to assess the level of CSC risk awareness of those functions.

Despite that the delay of project materials is always at the forefront of CSCRM, there has been no reference to the causes and the consequences of the delay of materials that are on the critical path of the PM schedule and have long lead time. The causes and the effects of the delay of materials have been investigated thoroughly through the years [42], [117], [118] although this has been done in a way that covers only generic pieces of equipment or materials without focusing specifically on equipment or material with high specialization like ultra large and heavy water high-pressure valves or high-spec gas turbines. The CSC process, when such pieces of equipment are required, demands different handling since the delay of such equipment on the project site will not only delay the whole project, but at the same time will bring upon significant consequences of economic nature. This is a risk that is connected with all the different themes that were detected in the LR (management, collaboration and relationships, technology, visibility) since it is affected by those and has direct implications on them.

5. Methodology

Empirical Setting

To serve the purpose of this thesis we will ask CSC professionals of an EPC contractor, hereafter called EPCC through a single case study based mainly in semi-structured interviews supplemented by secondary data gathered from construction projects, focusing mainly on those projects that demonstrated delays in critical material. The research is focused on one company, which constitutes the single case. However, the investigation of multiple projects within that company represents embedded units of analysis within the single case. That approach aligns with Yin's (2003) description of case study designs, where a single case study can have multiple units of analysis embedded within it [119]. The company serves as the overarching case boundary, while the individual projects are sub-units that allow for a more detailed level of inquiry. In EPC industry each organization follows different SC procedures, although the level of standardization of firms that get awarded with projects whose clients are very demanding is more or less the same. The selection criteria of this specific EPCC were firstly, the fact that it deals with projects of high standardization demand and secondly, the scale of those projects is adequate to consider it as a big construction firm with high project risk exposure. Additionally, the fact that this specific EPCC has an active portfolio of high-risk projects means that the company procedures still follow the demanding quality protocols.

Research Method

The research method utilizes the Bow-Tie model which identifies the event paths that lead to unfavorable outcomes and provides solutions on how these can the avoided. There are plenty of variables to this model although the essence is the same. The basic structure of a Bow-Tie model consists of the top event which is at the center of the diagram, the Fault Tree Analysis (FTA) on the left, which depicts the causes, and the Event Tree Analysis (ETA) on the right, which depicts the consequences. Both of those trees converge at the center towards the top event. The diagram basically shows that the top event is shared by multiple possible scenarios [120].

The context of the bowtie model in the Engineering Procurement Construction (EPC) industry where the construction organization is responsible for these three disciplines of a project. This specific industry has been selected due to its absolute involvement in the CSC process starting from the design of a project, moving to the acquisition of the required materials, until the fulfillment of the project's scope.

The bowtie model has three main parts as already mentioned. The FTA, the top event, and the ETA. After having identified the top event which is the delay of the critical path material with long lead time, and the time where control of the CSC process has been lost, next the causes that lead to this event and the consequences it produces have to be found. To do so, this thesis will try to give an answer to these sub-questions, namely:

1. *What are the causes that lead to the top event?*
2. *What are the consequences of the top event?*

The completion of the bowtie model also requires identifying the preventive barriers that cover the cause scenarios, and the recovery barriers that mitigate the magnitude of the consequences. Therefore, another two sub-questions emerge, namely:

3. *What are the preventive barriers?*
4. *What are the recovery measures?*

Data Collection

To answer these two research questions along with their two sub-questions we will collect data from SC professionals of the subject EPCC through semi-structured interviews which will be conducted in three rounds. The method of the semi-structured interview was selected since this is the more appropriate qualitative data collection method that it gives the ability to the researcher to understand the unique viewpoint of the interviewee since he has the autonomy to deviate from a strict questionnaire framework and delve into ideas that pop during the course of the interview [121] [122].

Interview questions can be found in *Table 6* Interview Protocol. Semi-structured interviews took place on September 2024 as in *Table 7* Roles of Interviewees - Interview Rounds - Presence Type, where 16 interviewees were asked for their input. The semi-structured interviews lasted approximately 2 hours each. The set up included one question that would help the investigator to identify the causes, one question for the preventive barriers, one question for the recovery measures and one question for identifying the consequences. Lastly, a fifth question was included in the interview asking the interviewees which stage of the CSC in the most crucial. The last question does not seek data for the bowtie per se but it aims at validating how close is the literature on the CSC process risk.

The interviews were conducted in three rounds and the analysis of the extracted data was run in parallel with data collection. The first round which included the questions in a semi-structured method our intention was to gather as much information as possible regarding the four sub-questions. In the second round, the risks extracted by the analysis of the first round's data were presented to the interviewees who had to validate those and provide their probability and impact to the organization. Moreover, in the second round, we gave interviewees the chance to provide additional data if any with the aim to reach data saturation and guarantee that all available data were gathered and no more could add further value to our research. Lastly, the third round included the presentation of data to the interviewees who were asked to verify its validity before proceeding with the analysis. In regard to interview time allocation, 70 minutes were dedicated to the first round. 30 minutes to the second round, and lastly another 20 minutes to the third round.

To identify the materials/equipment that according to the EPCC's records run the risk of delay, the interview questions focused on gathering data from different project types, geographical area of the project, the types of materials/equipment and their origin countries, and the logistics. The following table shows the cases from which we extracted the data.

Project Type	Project Area	Mat/Equip Type	Mat/Equip Origin	Logistics	Reasons of Delay
Marine Infrastructure	North Africa	Main Girders	China	CFR (port near project site)	1. Client delayed approving final design 2. Client delayed approving supplier

					3. Port congestion 4. Customs clearance delays
Marine Infrastructure	Middle East	SCADA+Modular Substation	Europe	DAP (contruction site)	1. This package was decided to split in two parts in order to avoid overloading one supplier and reduce lead time although, these two parts were needed to be installed at the same time. One of the suppliers delayed on delivering thus delaying both parts
Renewables	Europe	Steel PV mounting structure	Europe	EXW	1. Ukraine war created raw material shortage 2. Ukraine war made steel prices

					fluctuate on daily basis, suppliers were not able to support their current orders or provide offer for additional requirements. 3. Big demand locally in renewables sector, supplier treated Clients in priority based on previous cooperations
Renewables	Europe	Flexible cables	Europe	EXW	1. Damage at factory production line with no available alternative
Oil & Gas	Europe	Centrifugal Pumps	India	FCA (port near supplier)	1. Lack of sub-suppliers' management

					from supplier side 2. Quality issues in supplier's bought out items (sub-components) 3. Delays in delivery of supplier's bought out items (sub-components) at factory
Oil & Gas	Europe	HV Cables	Europe	DAP (construction site)	1. Quality issues in production (need for re-manufacturing of the defective cable) 2. Lost production slot (supplier needed to re-arrange the production sequence to accommodate the defective

					cable remanufacturing in parallel with their newly received orders)
Energy	Middle East	Electrochlorination System	Europe	DAP (construction site)	1. The supplier delayed ordering the materials required for manufacturing the system because this type of order was not significant for his scale 2. The supplier didn't procure on time a special tool needed for the commissioning

Table 5 Project Types - Material Types - Reasons of Delay

Secondary data was gathered prior to the interviews to set the knowledge stage around the EPCC activities which will support the questions' formation. This data was drawn by the interviewees and included the appropriate description of the top event, the clarification of the CSC process in detail and the level of involvement of the EPCC in this process, the types of projects the EPCC undertakes, the geographical regions of activity, the types of critical materials and their importance, and the roles and responsibilities of the stakeholders.

The professionals selected to be interviewed have significant CSC experience gained out of construction activities in projects of the EPCC under investigation in Marine projects like ports, harbors, jetties and offshore protection structures, while it has been actively involved in the Energy related industry by constructing upstream and midstream facilities for the Oil & Gas sector and various power generation plants. Civil projects in the form of governmental infrastructures as well as Dredging and Pipe Laying works appear in the portfolio of the EPCC on a smaller scale. The EPCC is mainly active in the gulf cooperation council (GCC) region and has built a strong network of partnerships with governmental entities, workforce, suppliers and intel providers throughout the years which has rendered it a reputable EPCC in its area of expertise. The following Table 6 shows the questions asked and their relations with the data that are needed to be extracted for the formation of the bowtie.

Due to the fact that we focus on a specific aspect of the CSC, and since more than one active or past projects were under the microscope of this research, we asked professionals with the same role to participate. In that way we enrich our data collection with insights from elite informants that under the same role that had been engaged in various projects. Therefore, we ensure that we capture a 360 view of the researched topic, reducing bias and increasing strengthening overall validity. Engaging multiple informants with same or similar roles that are engaged in construction projects we achieve data triangulation. to enhance the credibility, validity, and reliability of research findings by cross-verifying information from different angles, since based on literature data triangulation as involving "the use of heterogeneous data sources" and "gathering data using different sampling protocols [123]. Thus, aligning with the approach of collecting data from elite informants in various projects under the same role.

Interview Questions	Relation
What are the causes that lead to the top event?	Causes (FTA)
What are the consequences of the top event?	Consequences (ETA)
What are the preventive barriers?	Preventive Measures (Bowtie analysis)
What are the recovery measures?	Recovery Measures (Bowtie analysis)
Which stage of the CSC is the most crucial?	Literature validation

Table 6 Interview Protocol

The following table shows the roles of the expertise that took place in the interview, in how many rounds they were present, and which of those were conducted face-to face or online.

Roles	Interview Rounds	Presence
Procurement Manager (01)	3	Face-to-face
Procurement Manager (02)	3	Face-to-face
Procurement Manager (03)	3	Face-to-face
Procurement Manager (04)	3	Online
Logistics Manager (01)	3	Online
Logistics Manager (02)	3	Face-to-face
Logistics Manager (03)	3	Online
Procurement Category Manager	3	Face-to-face
Procurement Engineer	3	Face-to-face
Senior Procurement Engineer (01)	3	Online
Senior Procurement Engineer (02)	3	Face-to-face
Stores Manager	3	Online
Subcontracts Manager	3	Face-to-face
Construction Manager (01)	3	Online
Construction Manager (02)	3	Online

Project Manager	3	Online

Table 7 Roles of Interviewees - Interview Rounds - Presence Type

Data Analysis

Fault Tree Analysis (FTA)

The FTA is the first analysis that will be conducted. FTA helps in identifying the root causes of a system failure. It is a map that illustrates the sequential connection of all the possible faults with the failure and it supports decision-makers in risk management. The FTA diagram has a branching form which on its base has the basic faults that lead to a central major fault. Then, these major faults lead to the critical or top event. The basic and the major faults may or may not happen simultaneously because a basic fault is enough to lead to the top event.

Event Tree Analysis

Subsequently, the ETA is done which is used to explore all the possible outcomes that entail from the critical event including all the barriers that have or have not succeeded in limiting the consequences of the latter. ETA helps in determining if the preventive barriers are adequate to minimize the adverse effects.

Bow-Tie Analysis

Lastly, the Bow-Tie Analysis is a model that depicts the cause-and-effect relationship between the basic faults of the FTA and the outcomes of the ETA. In the center of the model is the critical event which is common to the FTA and the ETA. This analysis helps at identifying the safety barriers that prevent the critical event from occurring and the ones that act as recovery mechanisms after the critical event has taken place.

What is the CSC Process?

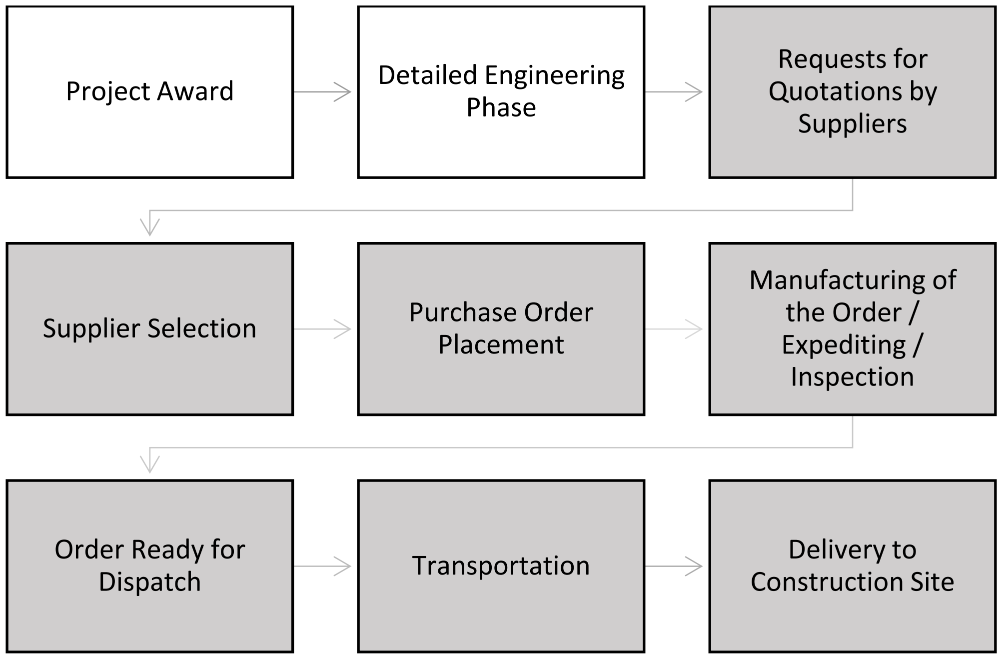

Figure 4 CSC Process

*(*the boxes filled with white color are not part of the CSC but greatly affect it)*

To make the CSC process most understandable the reader first needs to understand the process of project award. For that purpose, the following paragraphs will mention the stages of the project life cycle but without giving an extensive description of the processes that are not part of the CSC.

To start, a client, having figured out the concept of the project along with all the prerequisite technical parts, initiates a public tender where the potential contractors place their bids based on the cost they have stipulated during the tendering phase. At this phase, usually the tendering department of a construction firm aims at assuming the total cost of the project fulfillment, months or even years prior to project initiation. This is done by requesting budgetary offers from suppliers and sub-contractors, and by adding up those with the engineering and the construction costs that are usually done by the EPCC itself. The client though, does not require just a number to award a project but will demand various types of credentials of economic, quality, environmental social governance (ESG) and other nature.

In case of an award, the EPCC is responsible for the design of the project. The design includes the technical design and the materialization plan. The technical design can be outsourced. When the third-party designing firm delivers the drawings, the EPCC reviews them and approves them or sends them back to the designing firm for redesign. The final approval of the design is done by the client who can send the drawings back for redesign despite having been approved by the EPCC.

The finalization of the design marks the commencement of the actual procurement process and is the first stage of the CSC. During the tendering phase, the EPCC does not have a firm design on his hands. That means that there might be crucial differences between the initial and the final design, hence altering the material requisition. Additionally, the data provided by the suppliers during the tendering phase, mostly procurement cost and lead time, will be changed based on the final technical specifications of the materials/equipment. Therefore, the procurement department proceeds with requesting updated offers from the suppliers. The updated offers will most likely transform the project schedule and the project budget since they differ from the initial requests. The suppliers had given offers based on their production schedule at the time of the tendering process and since then the variables that are affected by the markets will have changed.

Upon receipt of the final offers by the suppliers, the procurement department selects the appropriate ones based on some criteria and issues the purchase orders (POs). From that moment up to the readiness of the material/equipment for dispatch, the procurement phase involves mostly two processes that track and monitor the manufacturing process. These processes are the expediting and the quality inspection. The former aims at tracking the progress of manufacturing, making sure the supplier follows the pre-agreed manufacturing path during specific stages and that he provides the EPCC with the appropriate documentation. The latter's scope is to make sure that the supplier meets the quality production standards so that the quality of the material/equipment under production meets the project's quality standards. Both of those processes are implemented to protect the project schedule from delays caused by the suppliers.

Considering that the manufacturing process has been completed, the material/equipment is then ready to be dispatched. Based on the supply agreement, the material/equipment is either picked up at the supplier's premises by means of transportation arranged by the EPCC or it is delivered by the supplier at its final destination. The Incoterms determine who will undertake the delivery. If the EPCC opts for an Incoterm that nominates the supplier as the responsible party for the delivery of the material/equipment, then the former might avoid the risk that the process of transportation hinders but the procurement cost will be higher since no supplier is willing to undertake the extra risk without extra reward. The Incoterm on a supply contract is a mutually agreed between the two parties. Some construction firms have adopted the policy to always procure with Incoterms that minimize the transportation risk while others prefer to maximize it in exchange for full control of the process.

The last stage of the CSC includes the delivery of the material/equipment at the construction site. This is the moment when the procured items are available for the erection activities supposing that the quality inspection that guarantees if the arriving items are suitable for installation and are built according to the material requisition has been completed.

What is the Definition of Materials of the Critical Path?

The materials or pieces of equipment of the critical path can be alternatively called "critical materials/equipment". A material/equipment is critical due to its importance on the project schedule since its delivery to the project site on time means that the project will not be timely affected. In other words, there is a relationship of dependence between the presence of the material/equipment at the project site within the time frame that has been predicted on the project schedule and the progress of the project.

The critical path in project management is the longest sequence of tasks or activities that determines the minimum duration a project needs to be completed. The tasks or the activities are dependent with each other because any delay in one of them will directly delay the next in the sequence and subsequently the project overall. Project management is the process of identifying and managing the above-mentioned tasks and activities in a way to minimize the cost and the duration of a project.

The criticality of the material/equipment is not based solely on its lead time, but on the relationship of it with the project's time frame. That means that, if for example the lead time of a critical material/equipment is 16 months and the project will be completed in 5 years, then the lead time of the critical material/equipment is not significant even if it would be delayed for 6 months. On the other hand, if the lead time of the critical material/equipment is again 16 months and the project is expected to be completed in 36 months, then a potential delay of the critical material/equipment of 6 months could derail the project schedule, hence, in this case the significance of the material/equipment's lead time is bigger. Therefore, the criticality of the material/equipment depends on its lead time in conjunction with the project's completion time.

Critical materials/equipment could be either a simple material like steel piles or a sophisticated piece of electromechanical equipment like a gas turbine. The reason behind why a simple material can be considered as critical as high-end equipment is because they may both play a crucial role in a project's critical path. For example, in a marine infrastructure project where the scope is to build a pier, the progress of works will highly depend on the availability of the steel piles at the project site. The same rule applies in an energy project where the scope of work is to build an electricity production facility which will utilize a gas turbine for the production needs. Obviously, the gas turbine per se is critical to the progress of works since it has a major involvement in the process, but this is not always the case. Major electromechanical equipment as such is usually designed as an all-in-one system. What that basically means is that the unit of the gas turbine arrives at site as a system that includes all its supportive systems like cooling, oiling, etc. In such cases, a piece of equipment like that is almost a plug-and-play unit, and a potential delay in its arrival at the site might not affect the total progress since the rest of the project's works can be continued.

Other materials/equipment that are usually the critical ones for a project include desalters, compressors, separators, substations, supervisory control and data acquisition (SCADA) systems, distribution boards, switchgears, substation control and monitoring systems (SCMS), pumps, piping, waste treatment systems and others.

What are the Roles and Responsibilities of the Stakeholders Involved in the CSC Process?

The roles involved in the CSC process can be categorized according to the functions of the various departments that act within it. The department that handles the functions of procurement, logistics and stores is the Procurement department (PRC) although, despite being responsible for the processes of those functions, it is not fully responsible for the causes or the consequences that relate to the critical event. The reason behind that is the fact that there are other stakeholders that provide input to the PRC throughout this process. These stakeholders include the Client, who has the upper hand in determining the requirements of the project which are subsequently passed to the Engineering department (ENG). ENG handles the design of the project and provides the PRC with the technical specifications and the volume or amount of the materials/equipment required. The Quality department (QLT), in the context of the SC process, checks that the material/equipment is produced according to the design standards, that the former has been delivered to the site in the required condition, and that it works. The Construction department (CON), having received the material/equipment, might provide further input to the CSC process at times when blockages to the construction process arise days or even months after the delivery of the material/equipment to the construction site. Finally, Suppliers play a crucial role in the CSC process since they provide perhaps the most valuable input about the materials/equipment. This input includes information about the production feasibility, availability, price and lead time.

It is evident that the CSC interfaces of a project are many, and the input provided by each of the stakeholders is not only crucial but also continuous. A depiction of those interfaces and the continuous data input can be seen in the below figure.

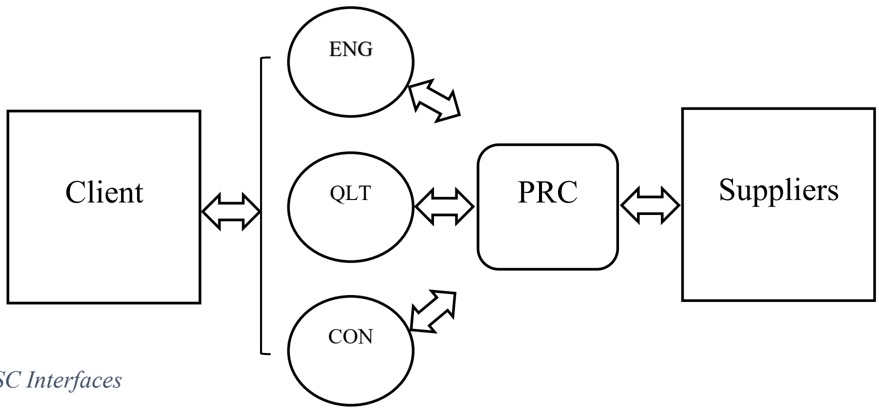

Figure 5 CSC Interfaces

A critical event is the result of a control loss. The critical event is derived by a cause and it leads to a consequence. The critical event under research is the delay of the delivery of critical material/equipment at the construction site. PM sets the "criticality value" of the task that includes a material/equipment. The "criticality value" depends on the sequential relationship of this specific task with the subsequent one which are both nodes of the critical path in the project schedule. Hence, the timely completion of these tasks is vital for the success of the project. This “criticality value” can vary throughout project’s materialization since unforeseeable events such as the design of the project or variation orders may occur. This basically means that a critical event may not be expected at the planning stage during early project’s life but should always be expected and evaluated in a new basis whenever the project is altered.

The basic fault scenarios depict the causal source of the top event. The delay in delivery of the critical material/equipment is caused by certain faults at different stages of the CSC which are under the control of different parties. Although, to facilitate the proper design of the FTA diagram, the structure approach has to be understandable and therefore, the major fault scenarios are wider. These are connected with an “OR” logic gate, indicating that the top event will happen in case one of these fault scenarios activates. Each fault scenario is a consequence of some basic faults which are the causes/threats that were identified from the interviews that are also connected with “OR” gates for the same reason.

6. Findings

Fault Tree Analysis

The sum of the basic faults is 37 and are depicted in detail in *Figure 6 FTA Diagram*. These basic faults form six major fault scenarios namely planning, management, manufacturing, logistics, post-delivery and force majeure. The following diagram depicts the FTA.

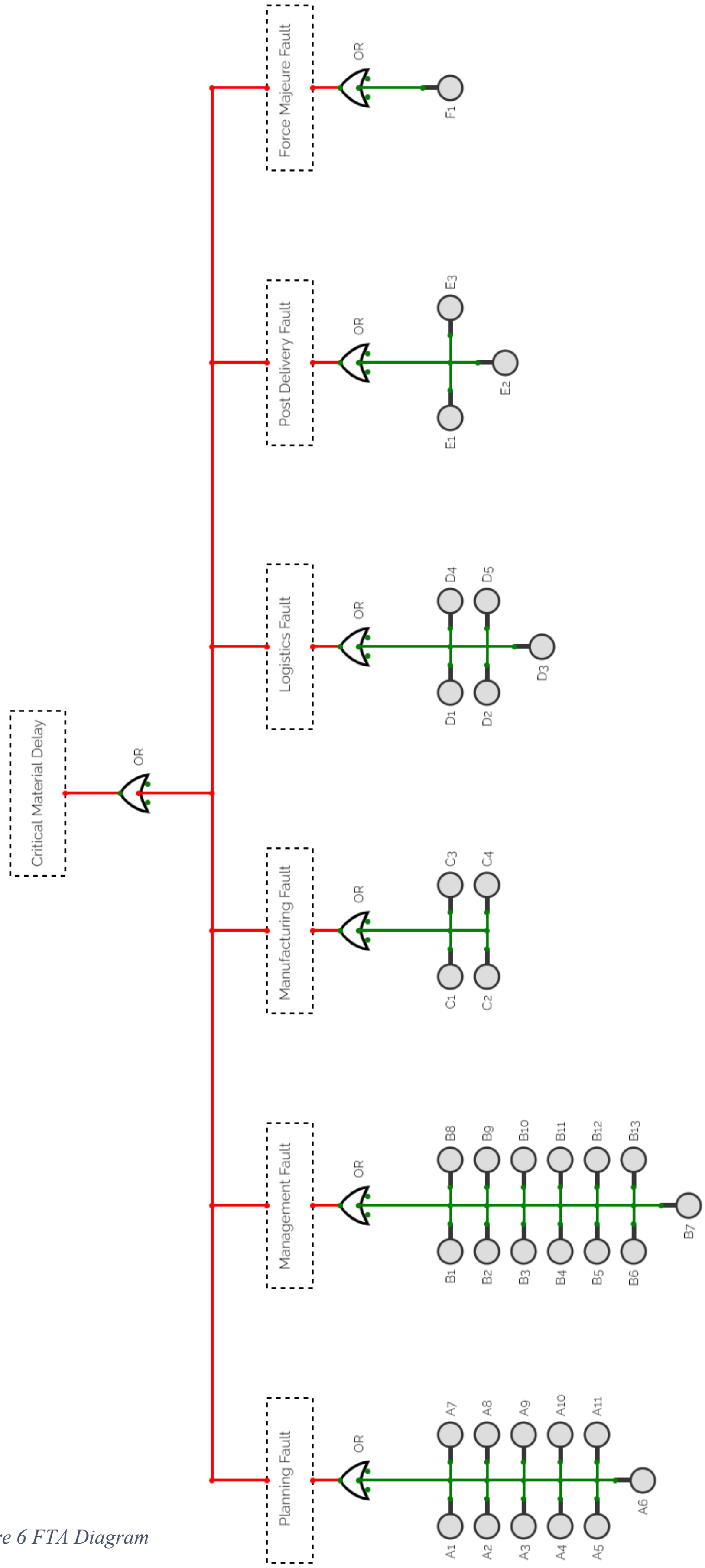

Figure 6 FTA Diagram

It is evident from the answers given by the interviewees that most of the causes/threats that lead to the delay of critical material/equipment derive from management related events followed closely by causes related to the planning of the project. There have also been identified other types of causes/threats which take place at subsequent stages of the CSC such as the manufacturing stage, the stage of logistics and the post-delivery phase. Moreover, the causes/threats could be sub-categorized based on which party of the CSC is responsible for the delays. These parties are the EPCC, the client, the supplier and the transporter/agent who undertakes the logistics, but this could be a subject for another research. Lastly, causes/threats for the delay of a critical material/equipment may be a force majeure event such as natural disasters, pandemics, strikes, and any other event which cannot be controlled by the parties mentioned. This fault category will be consisted by only one basic fault which includes any event that belongs to this category.

Planning fault

Planning fault is the fault caused by inaccuracies and deficiencies related to planning either during the detailed engineering phase or during the rest of the CSC phases for which either the client or the EPCC or the supplier is responsible due to the fact that project requirements can change throughout its lifecycle. The client, at the beginning of a project, provides the EPCC with a preliminary design which plays the role of the framework in which the EPCC has to produce the final design based on his expertise. As this is only a preliminary design, the EPCC, usually with the support of a third-party designing firm, aims towards finalizing it. Depending on the level of detail of the preliminary design, the size and the complexity of the project, the finalization time changes. In parallel, major or minor changes (depending on the level of client involvement) require the confirmation of the client. These design changes produce technical variations to the materials and the equipment planned during the tendering phase. Subsequently, lead-times, procurement costs and prerequisite woks change as well. In other words, if project plans wouldn't had taken all these changes into account, then no construction project would be viable. The term "float" in project management is utilized to express the extra time allowed for delays of the tasks on the critical path. Project managers though cannot let much float in a project and the reason is economic. In EPC and in most of the construction contracts payments take place at milestones that are related to the progress of the project. That means that a project manager, despite wanting to allow extra time for potential delays, does not want to put his company in financial troubles by not achieving the milestones on time.

Moreover, at the end of the detailed engineering phase when the project designs and the technical requirements for the materials/equipment have almost been finalized (except if issues arise during the construction phase), the suppliers get the requests for that materials/equipment. The issue here is that a significant amount of time might have passed since the moment the EPCC had contacted the suppliers for tendering purposes. During this period the market has most probably changed, some raw materials have become more expensive, and others have gone scarce. Lead-times may have increased due to high workloads; geopolitics might have rerouted the flow of goods and many other different variables may have played their role in producing SC delays which had not been considered at the initial planning phase. This leads to unrealistic construction scheduling and as a consequence, a new procurement strategy that corresponds to the new data might be needed. Also, design changes by the client may take place during the execution of the order and more time-consuming approvals may be necessary for those changes. Suppliers on the other hand might have not planned to have the appropriate raw materials in stock for the variation orders which increases lead-times dramatically.

Lastly, faults related to planning involve delays produced by lack of experience or expertise in handling newly introduced types of materials/equipment, markets, and processes or policies. Examples include poor scheduling for ordering extremely specialized materials/equipment, governmental restrictions which were unknown to the EPCC at the beginning of the project, and the undertaking of materials/equipment transportation for economic reasons.

Table 8 depicts the 11 basic faults that lead to a planning fault corresponding to the responsible parties.

Label	Planning Basic Faults	Responsible Party
A1	Ineffective project planning	EPCC
A2	Incomplete design during purchase order (PO) placement	CLIENT, EPCC
A3	Suppliers' need to source raw materials that they cannot find locally	EPCC
A4	Slow approvals for engineering and quality documents	CLIENT, EPCC, SUPPLIER
A5	Unclear or changing specifications can delay procurement	CLIENT, EPCC
A6	Poor estimation of materials quantity	SUPPLIER
A7	Inconsistent demand	EPCC
A8	Custom made Special Materials	EPCC
A9	Government restrictions	EPCC
A10	Unrealistic Construction duration	EPCC
A11	Variation and changes	CLIENT, EPCC

Table 8 FTA Planning Faults

Management fault

The category of management fault is relatively vague. The range of basic faults that are contained within it varies from inefficient processes and culturally affected strategies to financial troubles and lack of technological advancements and innovation. The 13 basic management faults that were identified focus on the late approval process when project variables change, the procurement strategy, the lack of employee motivation, financially driven decisions, and communication issues.

Elaborating on the above and starting with approval and review-cycle issues it is understood that the scale and the complexity of a project demands hierarchical approvals to safeguard technical correctness, financial clarity and distribution of responsibility. This process is per se a preventive measure for events that could lead to technical deficiencies, corruption and legal disputes with counterparties, but at the same time it produces delays on the CSC.

Other significant basic management faults derive from procurement processes and more specifically with the activities involved in the EPCC's strategy regarding suppliers and sub-contractors. Such activities include the selection of suppliers/sub-contractors, expediting manufacturing activities, communication, and management. The selection process is affected by multiple variables such as the type and the quality of the material/equipment or the service that the EPCC is looking for, the project's budget, the EPCC's commercial strategy, quality standards put by the client or regulations, and others. The general framework is put in place by the client and the local law. Clients look for contractors to complete projects with specific technical requirements. Special technical requirements demand special qualifications which the potential contractor must own in order to be awarded. Besides the technical know-how that the EPCC needs, he must operate according to specific quality standards. Such standards include the implementation of activities that are relevant to the procurement process. Subsequently and on the same path, the suppliers and the sub-contractors must operate under specific standards themselves so that to make trade relationships with the EPCC. The quality validation mechanism from the EPCC's side is the "supplier/sub-contractor assessment". An assessment though is not enough to make sure that the supplier will follow through with the manufacturing process flawlessly, therefore another mechanism has been adopted by the EPCC, the "expediting". These two mechanisms have been implemented in the procurement process to prevent delays either by avoiding to select inadequate suppliers or by gaining greater visibility of the manufacturing phase. EPCC's profitability though depends on the procurement cost and the cases where the contractor prefer cheap solutions over quality are not rare. This risk appetite culture is driven by economic advantages, but it sometimes leads to some basic management faults. Other basic management faults driven by economic criteria include the lack of experienced and motivated personnel and the shortage of human or technological resources.

Table 9 below depicts the 13 basic faults that lead to a management fault corresponding to the responsible parties.

Label	Management Basic Faults	Responsible Party
B1	Late procurement process initiation	EPCC
B2	Poor expediting activities	EPCC
B3	Delay in approving design changes	CLIENT, EPCC
B4	Poor communication between the parties	CLIENT, EPCC, SUPPLIER
B5	Difficulties in financing	CLIENT, EPCC, SUPPLIER
B6	Lack of top management involvement	EPCC
B7	Lack of experienced and motivated personnel	EPCC, SUPPLIER
B8	Slow decision making	CLIENT, EPCC, SUPPLIER
B9	Financial process delays	CLIENT, EPCC, SUPPLIER
B10	Shortage of resources	EPCC, SUPPLIER
B11	Selection of unreliable suppliers	EPCC
B12	Sourcing mats/equip from distanced countries	EPCC, SUPPLIER
B13	Complex review cycle	CLIENT, EPCC

Table 9 FTA Management Faults

Manufacturing fault

A manufacturing fault is the most straightforward type of fault that can produce the top event. The basic faults that comprise this category are related to the manufacturing process considering that the technical requirements for the materials/equipment have been finalized and provided on time. Mistakes done by the supplier could sometimes be avoided if the supplier assessment and the expediting activities were successful although, sometimes suppliers make mistakes even if the aforementioned activities were done according to the standards. Moreover, some other activities such as inspection of the ordered equipment at supplier's premises and factory acceptance tests (FATs), need regular follow-ups by the EPCC despite having agreed on a production schedule with the supplier. The reason of delay of those follow-ups could be due to either party's fault.

These faults are not part of the planning category since this research extracted data from the EPCC's side whose scope is to analyze the risk that he can manage. Many other related to the manufacturing process causes of delay could be identified if those questions were asked to professionals that work for a supply company.

Therefore, 4 basic manufacturing faults have been identified and are projected in the following Table 10.

Label	Manufacturing Basic Faults	Responsible Party
C1	Mistakes and deficiencies during manufacturing by the supplier	SUPPLIER
C2	Testing and inspection activities not done on time	EPCC, SUPPLIER
C3	Delay of material delivery at supplier's premises and loss of production slot	SUPPLIER
C4	Damage at supplier's production line	SUPPLIER

Table 10 FTA Manufacturing Faults

Logistics fault

Construction logistics has only recently been an area of interest for construction companies due to high risk and cost factors that affect a project's budget and schedule. Traditionally, construction companies preferred incoterms which put the transportation risk on the supplier's side in spite of the higher procurement cost. Some specific types of equipment that need special handling or in cases where the supplier has a better knowledge of specific types or transportation and regions, it is preferable to trust him with the logistics undertaking. Some construction companies though have developed in-house logistics know-how that allows them to take over this process and reduce the total procurement cost. Besides that, the higher the visibility, the higher the control you have over a shipment.

Logistics could be proved to be a major bottleneck for the CSC since it is directly connected with whatever is related to the global trade. Sea route changes due to terrorism, canal blockages, shortage of shipping equipment such as containers, port congestion, and delays at customs facilities are usual causes of delivery delays.

Lastly, is has been observed that international shipments regularly delay due to inaccurate or absent proper documentation which may be caused by every party involved in this process. Logistics fault causes extracted are summarized in the following Table 11.

Label	Manufacturing Basic Faults	Responsible Party
D1	Leaving the logistics on supplier's side (DAP, DDP, etc)	EPCC, SUPPLIER
D2	Handling (transport wise) complex equipment	EPCC, SUPPLIER
D3	Congestion at ports, shortage of shipping equipment and customs clearance delays	3^{RD} PARTIES
D4	Interruption in Carrier Services, Marine routes change, roadblock, Carrier Service Suspension	3^{RD} PARTIES
D5	Documentation delays	EPCC, SUPPLIER

Table 11 FTA Logistics Faults

Post-delivery fault

Post-delivery fault takes place after the actual delivery of the materials/equipment at the construction site. The process of the CSC ends when the materials/equipment arrive at site in proper working condition. In some cases though, this proper working condition is only confirmed when the site acceptance test (SAT) takes place and everything has gone according to the plan. In case the SAT is unacceptable, then the materials/equipment are not considered arrived and the CSC process has not ended. The SATs are needed in order to test the procured item on site conditions which may differ from the factory ones. For example, a hydroelectric generator may be proved to be in a working condition when tested at the controlled environment at supplier's factory but could fail to meet the site standards due to different working conditions.

Additionally, during the commissioning stage, where for example the whole hydroelectric plant is tested, many factors may produce delays such as commissioning fails, client's demands on the process to protect his interests, supplier's representatives' attendance unavailability, and negotiations after the identification of a fault.

The following Table 12 depicts these basic post-delivery faults.

Label	Post-delivery Basic Faults	Responsible Party
E1	Failure of site acceptance test (SAT)	EPCC, SUPPLIER
E2	Commissioning parties' attendance difficulties	EPCC, SUPPLIER
E3	Client's involvement at commissioning	CLIENT, EPCC

Table 12 FTA Post-Delivery Faults

Force majeure fault

Last major fault category is the force majeure fault. This category includes basic faults produced by unforeseeable events, outside of the sphere of influence of any of the involved in the CSC parties. Such events are natural disasters, geopolitical tensions, pandemics strikes, etc.

These events, being unforeseeable, will all be contained into one basic fault as depicted in following Table 13.

Label	Force Majeure Basic Faults	Responsible Party
F1	natural disasters, geopolitical tensions, pandemics, strikes, etc.	3RD PARTIES

Table 13 FTA Force-Majeure Faults

Event Tree Analysis (ETA)

The initiating event for the ETA is the delay of the critical material. In ETAs, the potential consequences of the initial event are analyzed based on the results of the mitigation measures. In construction projects, the steps that can be taken in case a critical material delays are specific and not many. Of course, the significance of the delay may vary from slight to high. In general, a delay of up to a week is considered normal in the CSC, but a delay of three months is significant. The delay though depends on the specific conditions under which the project operates. In other words, it depends on the progress status of the project if a delay of one day is considered significant or if a delay of three months is considered normal.

Figure 7 ETA Diagram below does not take into account what the amount of delay is, but it provides the different outcomes produced for the EPCC depending on the success of the barriers put to mitigate the damage.

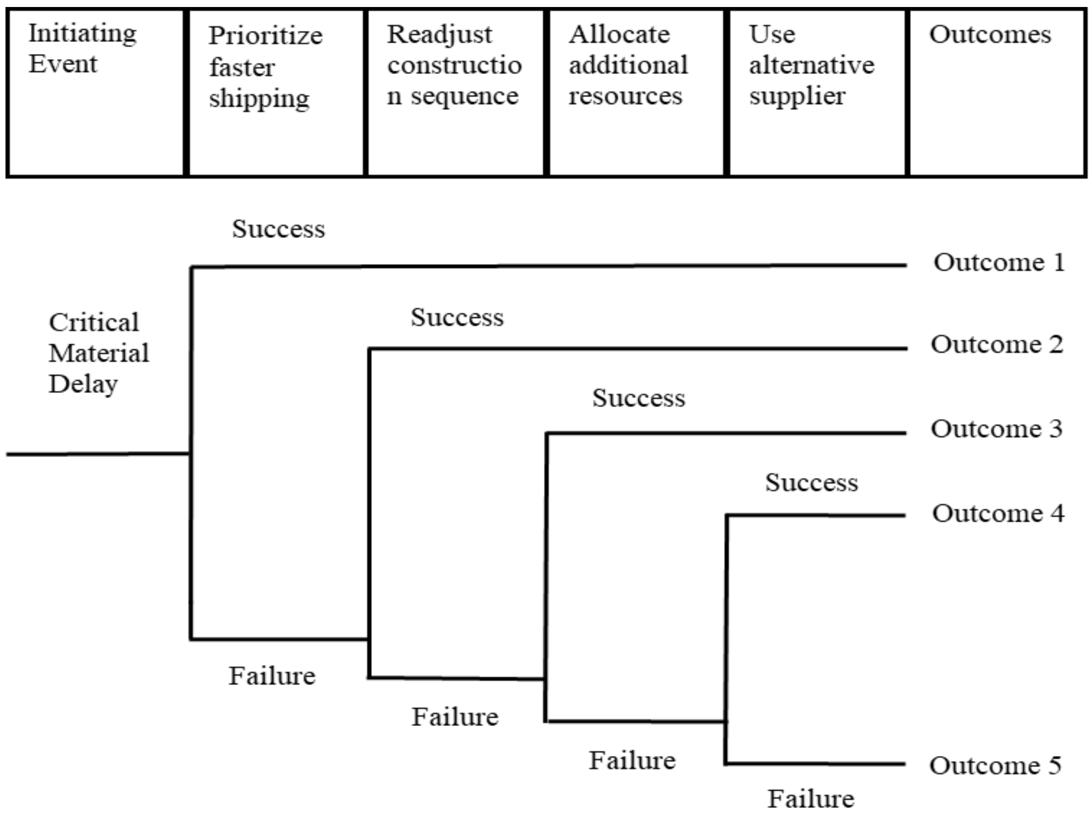

Figure 7 ETA Diagram

Based on the analysis, the recovery measures that could mitigate the delay were few, and their significance increases as the options get less. In other words, the less the available mitigation options, the more drastic are the measures that can be taken. A project management plan is dynamic which means that whenever a project variable such as a critical material, a sub-contractor, the client, and others provide new input, the project plan changes. The ETA does not consider the outcomes of a dynamic system but rather a static's one. This is the reason why the barriers are put in order. In a dynamic system, the sequence of the barriers would change according to the status of the project at a specific moment. If for example the delay of the material was known at a very early procurement stage, then the use of an alternative supplier could be easier in contrast to a late stage.

The first barrier in sequence is the prioritization of faster shipping method. This barrier precedes the rest since this measure is the most common in cases of material delay. Certain parameters though such as the type and the size of the material/equipment play crucial role since no everything can for example be transported by airplanes, which is considered the fastest shipping method. The shipping method is also affected by the incoterm agreed within the EPCC and the supplier, but this can be negotiated in case of delay. If the incoterm dictates that the supplier is responsible for the delivery of the material/equipment, but he is also the party which caused the delay, then the EPCC has the negotiation leverage to demand a faster shipping method. Contrary to that, in case the incoterm dictates that the EPCC is responsible for the transportation part of the shipment, then he has the freedom to select the fastest shipping method although bearing all the additional shipping cost. If this barrier is successful, then the reduction of shipping time may offset the time loss during the manufacturing process but that depends on the amount of it.

The next barrier is the readjustment of the construction sequence. Depending on the progress of the project, the criticality of the delayed material/equipment, and the complexity of the subsequent activities in the project schedule, readjusting the construction sequence can be proved to be impossible. If readjustment is possible and considering that the readjusted activities would be completed the same moment when the delayed material/equipment will arrive at the construction site, then the project will not delay. This is rare due to the fact that the criticality of the material/equipment is driven by its involvement on the project schedule and the works needed to be done prior to its arrival, and not for the functionality of it in the completed work. Readjusting though the construction sequence is sometimes a matter of luck since new schedule has to be agreed between the EPCC and the sub-contractors who will undertake the activities that are rescheduled. This can be very complicated since these sub-contractors not only have to be available but will also be asked to find the required resources earlier than expected.

The third barrier, similarly demanding in terms of cost as the second one, is the allocation of additional resources by the EPCC. When the first two barriers have proved to be ineffective, the EPCC will try to activate additional resources such as manpower and construction equipment. By accelerating other project phases that do not rely on the critical material through the introduction of multiple shifts, parallel works and the maximization of equipment utilization, non-critical path activities which may have been scheduled for later stages will be completed faster. The most effective advantage though is that the resources that will be needed for the completion of those non-critical path activities will be utilized for those instead of being idle due to the critical material/equipment delay, and when the latter will arrive those will be freed up and will be utilized again. Again, this technique might somehow mitigate the impact of delay but in general it will not eliminate it. Moreover, this allocation will certainly produce extra costs and there has to be a justification for such step.

The fourth and final barrier is the usage of alternative supplier. This is the most complex and difficult decision an EPCC can take. The technical compliance, the quality standards of the alternative supplier, the contractual challenges with the first supplier, the new SC data, the various cost implications for the alternative purchase, the new approval cycle, and the coordination requirements with the engineering and the construction teams are some aspects that introduce a new set of risks and will only be considered if all previous steps have been exhausted.

The ETA has identified 5 outcomes, each with each own impact on the project and on the EPCC as business entity. As already mentioned, the magnitude of the outcome is absolutely connected with the degree of delay and its effect on the project's schedule. This sentence aims at clarifying that this ETA considers an average case of critical material delay and depicts the data that the EPCC who participated in this research has provided. In this particular case, the scale of damage by the delay increases as each barrier fails to minimize the loss. The scale is somehow exponentially increasing and may lead to catastrophic results not only for the project but also for the business itself. There have been set five different delay scales starting from insignificant up to catastrophic. Additionally, extra issues arise depending on the consequent barrier failures.

Outcome 1

Outcome 1 is clearly the most desired one since the delay is mitigated by the selection of a faster shipping method. For example, the initial plan was to transport the delayed material/equipment with a ship, but the urgency of the situation dictated a faster shipping method therefore, the project team opted for an air transport. The span of the delay magnitude may be from insignificant for delays of up to a month since such delay could be balanced out with an air transport, up to moderate for delays that exceeded the one month which the faster shipping method could only partially balance out. The increased logistics cost though cannot be considered insufficient since air transportation is not the most cost-effective method and air freights, especially for large and heavy cargo, may increase the total purchase price for more than 10%. It is notable that the project's profit margin decreases with such drastic measures.

Outcome 2

Outcome 2 is the second most desirable outcome in case of critical material delay. If the first barrier has not produced any positive result, then it is time for the project team to make some readjustments on the construction sequence. It is worth mentioning that the barriers 1 and 2 could both be activated at the same time depending on firstly the delay severity and secondly on the project progress at the moment the delay was known. For example, if the critical material was expected to arrive at site at a later project stage where no other construction activities were left to be done, then no readjusting could take place. The span of the delay magnitude, similarly with outcome 1, is from negligible for delays that could be offset by possible and effective construction sequence readjustment, to moderate where there are not many readjustment options to be considered. However, all this rescheduling comes with a cost such as contractual changes or even new agreements with sub-contractors, the withdrawal of workforce and equipment from one activity and their utilization for other ones, the inefficiency produced by the spatial congestion of too many workers and equipment, and others.

Outcome 3

Outcome 3 is less desirable than the previous two although there is still some margin for delay. The barrier of the allocation of additional resources can again be activated in parallel with the previous two barriers since these are not dependent on each other. The degree of delay can be significantly reduced by utilizing some extra workers in order to progress with the development of subsequent construction stages which will ultimately compensate for the time lost from the material delay. However, this barrier is not straightly connected to the material itself because it serves as a supportive measure. This barrier also comes at a price. Extra wages, overtime, more equipment rentals, and increased rates paid to sub-contractors who exploit the urgency of the situation to gain more profit are some of the additional construction costs that the EPCC is called to pay to balance some of the delay out. But the delay at this point can usually be reduced slightly depending on the type of project. In projects where civil works make up for the greater percentage of the project then such step is very efficient. On the contrary, in energy projects, where most of the works depend on the presence of the critical equipment at site, additional resources do not help the situation and idle time is inevitable. Besides adding extra construction resources there is also the option to support the supplier on his work and speed up the manufacturing process. Such step can be achieved either by giving performance incentives and by requesting liquidated damages, or by even assigning the co-manufacturing of the material to another supplier. Of course, all those solutions will firstly have to be included in the supply contract. This is called "exit strategy" and it ensures that, in cases of disruption, there will be continuity. This barrier stands as the last barrier of the relatively safe mitigation measures. This is the moment where the client is informed by the EPCC of the produced delays, and it is time to reconsider the project time schedule. Significant manufacturing delays of long-lead items are mostly a result of outer disruptions such as shortage of raw materials or global supply chain disruptions.

Outcome 4
Outcome 4 marks the point where the material delay has already produced a wide variety of serious consequences which could not be mitigated by the exploitation of additional resources. In general, it is considered impossible to seek alternative solution for a long-lead item that is part of the critical path of the project. To start with, the suppliers of such equipment are major manufacturers who might be even bigger businesses than the EPCC itself. Legally and economically wise, termination of a supply agreement for such packages is a very painful process and in most cases the remedy to the problem that would lead the EPCC to such drastic measures is not the path of litigation. The EPCC would firstly have to have agreed on certain contractual terms and conditions with the initial supplier that would cover as many fault scenarios as possible and would ensure that, whatever the case may be, the progress of the manufacturing works will continue. Outcome 4 though means that a major delay has occurred. The EPCC is close to pay or pays liquidated damages caused by the project delay and focuses on speed up the manufacturing process as much as possible.

Outcome 5
Lastly, outcome 5 is the most catastrophic occurrence of the possible ones. Of course, for such outcome to be possible, every possible aspect of the CSC must have gone wrong. Every delay mitigation barrier has failed to put the project back on track and the consequences may include reputation troubles for the company and its employees, the EPCC may be blacklisted by clients, the company might fail to pay off debts, and in

general face a commercial and economic crisis that could potentially lead to business cessation.

Outcomes	Description
Outcome 1	Insignificant to moderate project delay, Additional logistics cost
Outcome 2	Negligible to moderate project delay, Additional scheduling issues
Outcome 3	Moderate to high project delay, Additional construction cost
Outcome 4	Major to catastrophic project delays, High construction cost, Additional procurement workload, Contractual issues
Outcome 5	Major to catastrophic project delay, High construction cost, Contractual issues, High financial trouble, High reputational damage, Costs might be returned in case of Force Majeure

Table 14 ETA Outcomes

Bow-Tie Analysis

The 6 primary faults that were identified in the FTA are the threats on the left side of the Bow-Tie analysis. Accordingly, the 5 possible outcomes that were identified in the ETA have been categorized into 4 groups of consequences and can be seen on the right side of the diagram. For the purpose of the analysis, the selected loss event is the moment the delay of the critical material/equipment is known (*Figure 8 Bow-Tie Analysis*). The safety measures that would, a priori and a posteriori, minimize the possibility of the loss event and its impact are the preventive barriers and the recovery measures respectively. The process safety strategy proposed by Hendershot DC in an article about the chemical process safety strategies introduces four types of risk reduction approaches: inherent, passive, active and procedural [124]. Both the preventive barriers and the recovery measures were categorized respectively in *Table 15* Bow-Tie Analysis Preventive and Recovery Measures.

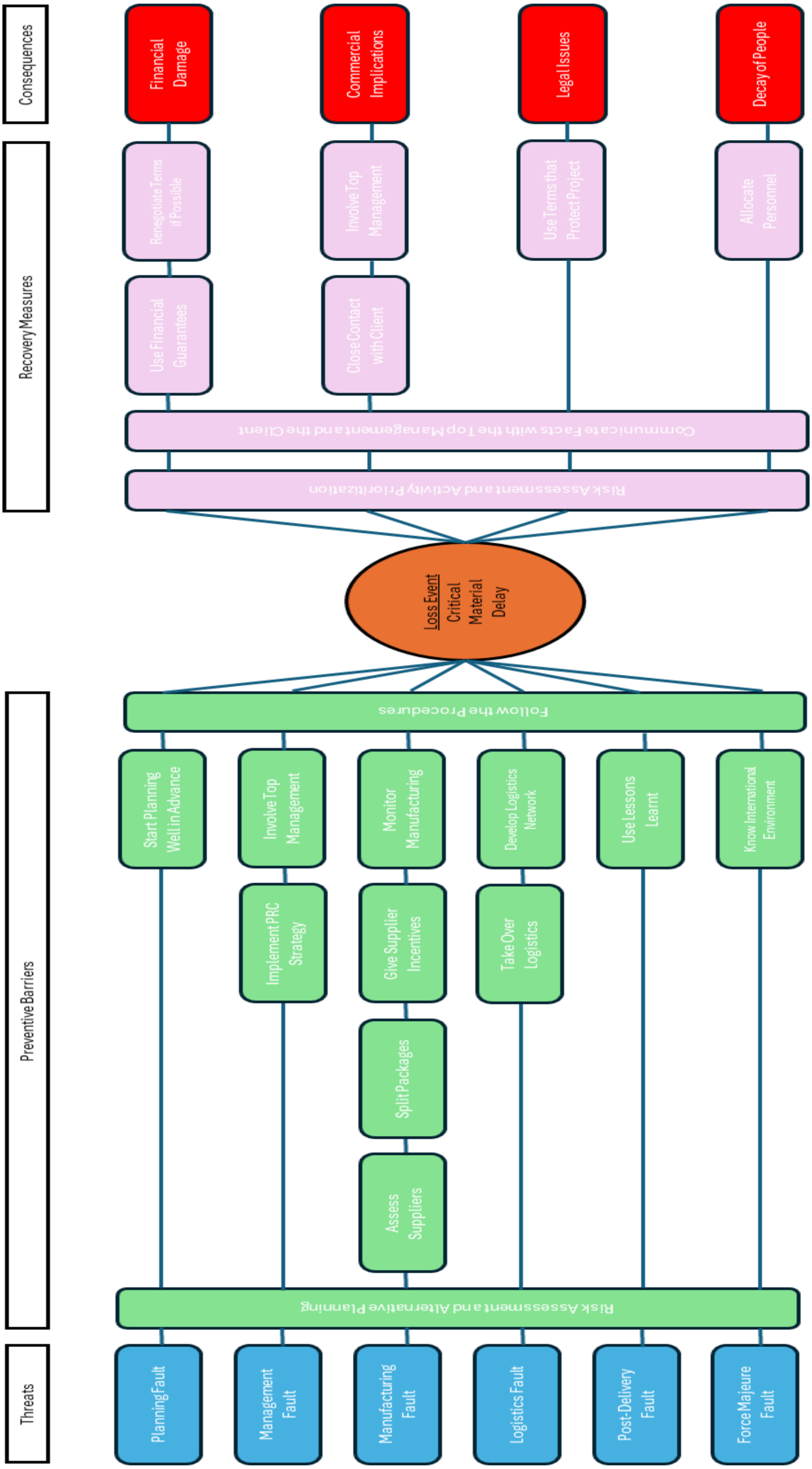

Figure 8 Bow-Tie Analysis

Measures and Approaches

Measures		Inherent	Passive	Active	Procedural
Preventive	Risk Assessment and Alternative Planning				X
	Assess Suppliers		X		
	Split Packages to as Many Suppliers Possible		X		
	Implement Properly the Procurement Strategy				X
	Give Supplier Incentives		X		
	Take Over Logistics	X			
	Start Planning Well in Advance		X		
	Involve Higher Management			X	
	Monitor Manufacturing				X
	Develop a Logistics Network		X		
	Use Lessons Learnt from Previous Faults				X
	Know International Environment		X		
	Follow the Procedures				X
Recovery	Risk Assessment and Activity Prioritization				X
	Communicate Facts with the Top Management and the Client			X	
	Use Financial Guarantees		X		
	Keep Close Contact with Client		X		
	Renegotiate Terms if possible			X	
	Involve Top Management			X	
	Use Terms that Protect the Project and the Company		X		
	Allocate Personnel and Tasks Properly				X

Table 15 Bow-Tie Analysis Preventive and Recovery Measures

The purpose of the inherent safety approach is to increase safety by removing hazardous situations from the system. At first sight, only the in-house handling of the logistical stage of the CSC is such a measure, although, depending on the procedures of each company, such measure can be considered a passive measure in case it has already been implemented. Another inherent approach would be a measure that dictates to always prefer sourcing materials/equipment from suppliers that score above a certain limit on the suppliers' assessment tool but, the implementation of the assessment per se stands as a passive safety measure. The result of those two measures is the same. On the one hand, the hazardous condition, which is the sourcing from suppliers with low scoring, gets replaced by suppliers with high scoring, but on the other hand, the implementation of such tool automatically rejects suppliers with low scoring. Therefore, the measure of implementing an assessment tool is the passive approach and the strategy of sourcing only from high scoring suppliers is an inherent approach.

The passive approach measures are the most among the others. This type of measure minimizes hazards using process features with the aim of minimizing the possibility of an adverse event to happen or its impact pro-actively. Besides the assessment of the supplier that was mentioned in the previous paragraph, there are many other preventive and recovery measures that can be considered as passive ones. Splitting one package to more than one supplier is such. Sourcing a critical system such as the fire-fighting system for an O&G project from multiple suppliers can spread the pressure of the SC by dividing the risk to as many manufacturers as possible. Similarly, giving your suppliers incentives for on-time delivery can reduce the chance of material delay. It is obvious that the supplier is obliged to deliver according to the agreed schedule, but incentives for faster delivery, if needed, may prove helpful. The same approach is followed by initiating the project planning activities relatively earlier than they traditionally start. The importance of this passive measure lies in the fact that time can be saved when the CSC process begins earlier than initially stipulated. If this happens, certain CSC delays might be foreseen, and further actions can be routed into the project's schedule.

On the same path, the development of a logistics network of partners can passively prevent the impact of a logistical fault but the prerequisite condition is that the inherent measure of logistics takeover must be in place otherwise this network has almost no use. The EPCC, by having developed such a network, not only would he have access to important market insights like which ports are congested, what routes are more suitable for his shipments and what are the levels of the freight rates, but he would also find logistical solutions that could reduce the risk of that activity. The advantage of being informed about the international environment is also a passive measure that can be applied to the whole CSC apart from the logistics activities. This measure is difficult to implement since it requires multiple sources for abstracting various market insights.

Ultimately, this information variety, when properly translated, is a benefit for every business in every industry that results in more opportunities and less risk.

Agreeing on terms that protect EPCC's interest in the contracts with its counterparts such as the suppliers, the sub-contractors and the clients is, in essence, a passive approach to risk reduction. As part of the recovery measures, these terms aim at establishing a legal fallback for situations which are adverse although can be foreseen based on past circumstances. Such situations are the delay of the delivery of the critical material by the supplier. A term that secures the EPCC from assuming the whole load of such an event is liquidated damages to the supplier based on the duration of the delay. Such a term aims at balancing the damages that must be paid by the EPCC to the client in case of a milestone delay. Performance bonds can also passively protect the EPCC in cases where the supplier does not meet his obligations as per the supply agreement. These obligations include the quality of the product and its on-time delivery. Its passive nature lies behind the fact that the supplier will try to deliver the product according to the itinerary in order to not lose the value dictated by the bond.

An interesting point highlighted by many of the interviewees was that not many things are left to do to change the course of a critical material delay. This stems from the fact, as previously explained, that the sourcing of a long-lead item is a complex process, and since the delay has occurred, only a few active measures can be taken. The active approach involves measures that are triggered when a certain condition is met. In contrast to the passive approach, the measures included in the passive approach react to the adverse event and aim at mitigating the risk produced by that. The first active measure is to escalate the issue to higher tier management supposing the lower-tier levels are incapable of resolving the new issue. This active approach, which can be used as both a preventive and a recovery measure, may or may not resolve a delay but chances are higher for successful mitigation since higher management positions have a firmer commercial understanding of the situation and perhaps a stronger negotiation leverage which could protect the EPCC from a bad or even worse state.

The last of the few active approach actions that are available include the communication of the new facts with the client, and, if possible, the renegotiation of the terms with him. Informing the client about the change of status of the project caused by a substantial delay in critical material/equipment is of high importance. Adverse events can hinder major suppliers that subsequently can delay or even postpone mega projects. It is critical that the moment this event is known to the EPCC the client is aware of the situation to pave the way for new project schedule rearrangements. The client expects to be informed of the situation early enough so that he can proceed with decisions that are above EPCC's influence. Besides the communication part, the contract between the EPCC and the client stipulates delay scenarios which have to be acknowledged by both ends if they happen. Contract renegotiations with the client can only happen under very specific circumstances and are in general hard to achieve. One of these cases can be if the critical equipment that has delayed has been "free issued" by the client which means that the sourcing of that equipment was not the responsibility of the EPCC therefore, the EPCC did not have any control over it.

Procedural approach measures, as the name suggests, are administrative controls or procedures that do not request any input to function. They are placed within specific CSC activities to provide adequate risk management in a systematic way. Procedural measures include frequent risk assessment and contingency planning and internal auditing for ensuring that the procedures of certain functions such as the procurement are followed as required.

Risk Calculation

The level of risk produced by the delay of the critical material/equipment was calculated based on the effectiveness of the recovery measures. The possibility of the occurrences along with their impact were evaluated based on four factors namely Financial, Reputation, Legal, and People. A relevant risk matrix (*Table 16 Risk Matrix*) was developed based on data extracted by the interviewees in the second round of the interviews. These were finally validated in the last round of the interviews. The risk level was determined by the equation of Risk = Probability x Impact. The risks were subsequently categorized in four ranking groups based on the result of the equation. These groups are low, medium, high, and very high, where different action requirements are demanded for each group. *Table 17 Measures and Urgency Level* below depicts the urgency level of measures.

	Financial	No impact	Minor extra costs	Significant extra costs	Damages paid to client	Bankruptcy
	Reputation	Minor impact	Fixable impact	Damage relationship with client	Industry wide impact	Internationa l impact
	Legal	No issue	Slight issue	Mediation	Arbitration	Litigation
	People	Normal workload	High workload	Excessive workload	Burnout	Resignation s
	Score	1	2	3	4	5
Score	Level	Insignificant	Negligible	Moderate	Major	Catastrophi c
5	Almost Certain	5	10	15	20	25
4	Likely	4	8	12	16	20
3	Possible	3	6	9	12	15
2	Rare	2	4	6	8	10
1	Unlikely	1	2	3	4	5

Table 16 Risk Matrix

Group of Risk Level	Risk	Urgency of Measures
15-25	Very High	Urgent Measures Required
10-14	High	Immediate Measures Required
5-9	Medium	Organizational Measures
1-9	Low	Procedural Measures

Table 17 Measures and Urgency Level

Lastly, *Table 18 Consequences and Risk Level* shows the risk level of each of the consequences according to the values of risk determined by the equation.

Risks	Probability	Impact	Risk level	Risk
Financial Damage	4	4	16	Very High
Commercial Implications	3	3	9	Medium
Legal Issues	4	3	12	High
Decay of People	2	4	8	Medium

Table 18 Consequences and Risk Level

As Table 18 suggests, the delay of the critical material/equipment can lead to consequences ranging from medium and to very high-risk level. The impact to the commercial status of the EPCC and its people cannot be in significant jeopardy since these EPCC's characteristics are protected by adequate preventive barriers and recovery measures. Moreover, such delay can never be the reason of significant damage to those two characteristics because of its nature. The commercial status of such a business can be affected by low-quality functions which in combination with each other can result in a low-quality service. EPC type of contractors take on significant risks since they handle three major disciplines (Engineering, Procurement, Construction). Each of these disciplines comes with their own processes and complexities that require a certain level of expertise. Essentially, a simple delay, even of a critical material, notwithstanding the fact that can delay the whole project and produce significant costs, cannot directly affect the commercial status of the contractor in a major or a catastrophic way. In other cases though, such delays may prove to be the cause of a major or a catastrophic commercial damage in an indirect way as if simultaneous delays of critical materials happen to multiple projects which result in liquidated damages paid to the clients that subsequently result to cash-flow shortages, and so on and so forth. Commercial implications received a risk level value of 9 in the condition of the delay for the reason that, firstly, it is possible for the relationship between the EPCC and the client to be damaged by a delay of a critical material, and secondly, because the impact by such event is not negligible. The risk level value of this factor, however, depends on the strategic importance of the specific client for the contractor.

The effect a delay of a critical material may have on people resulted in a risk level value of 8 which was produced by a rare probability with a major impact. A critical material delay may lead to high workloads for people work in the procurement departments in the search of alternative materials or suppliers, for project managers that seek resequencing solutions, for finance managers who take budget allocation decisions, and top management people who communicate the facts with the clients and work towards keeping the relationship untouched. The fact that health and safety, espacially for cosntruction companies with high standards, are regarded as top priority concerns, this seems to be an atiitude focusing mainly in the construction operation. However, the health of the employees that work in office jobs for construction companies is difficult to be considered as risky as the health of the workers of the field due to the nature of the perils. Some events of the significance of the top event under investigation rise the employee stress levels to a degree capable of bringing severe underlying health issues to the surface.

Legal issues can vary from minor breaches to fundamental ones. The former category may, among others, include the late submission of reports and documentation, the substitution of non-critical materials without approval, and minor delays in meeting non-critical milestones. On the other hand, the latter category may include the use of substandard materials, the failure to meet performance specifications, and the failure to meet critical completion milestones. The risk of legal issues was evaluated as high with a degree of 12. The effect that a critical material delay has on the judicial hypostasis of the contractor might be considered moderate, nevertheless, the probability of a legal issue arising due to such delay is fairly high. The involvement of the critical material to a project is multidimensional. Besides its complicity to the construction activities, the critical material's arrival at the site, its installation, and its good performance during the commissioning phase will most probably be some of the critical milestones on the contract with the client. The contractor's aim is to fulfill his contractual obligations on time so that he will be paid. The client on the other side wants the project to be completed on time to start exploiting the facility for commercial use. The more the project delays, the later this exploitation will start. The client will start loosing income by that late start, hence, he will demand compensation in the form of damages.

Primarily, legal consequences have financial impact on the contractor and thus, legal and financial consequences may inevitably fall under the same group of consequences. The reason, nonetheless, why it was decided to make two discrete groups for those two consequences is because a critical material delay can lead to legal friction between the contractor and his counterparts with subsequent financial effects and vise versa. Therefore, the financial damage due to a critical material delay may and may not be directly linked to the delay. In other words, financial issues arise either by the direct result of the delay or by its legally produced consequences. Consequently, this approach helps in setting separate risk reduction measures for legal and financial consequences.

Financial damage received a risk level value of 16. The risk for financial damage is considered very high because the probability of facing financial issues due to a critical material delay is more than possible and its implications are major. The delay of a critical material is in the heart of the contract between the EPCC and the client since it directly affects the total project duration, moving further in the schedule the critical milestones. Thus, this fundamental breach results in liquidated damages due to delay which ultimately influence the EPCC's profit and cashflow. Some of those costs may be balanced out by the liquidated damages the EPCC will claim from his supplier based on their in-between contract, but still, those may not be enough to compensate other costs like the payments of the idle workers and the damages for the delay to the sub-contractors. Some EPC contracts may also involve performace bonds or other types of guarantees to the banks, retention monies, idemnity, or other types of compensation clauses which the client deserves to activate in cases of breach. At the same time, financial damages may be caused by third parties which claim damages due to this delay such as the sub-contractors, consultants, engineering companies, equipment rental companies, logistics companies, local authorities, and whatever other entity that has been affected by this delay.

7. Conslusion and Managerial Implications

The literature on the topic of construction supply chain risk covers various perspectives but has omitted to explore how the delay of a critical material affects a construction organization as a business. This thesis represents a qualitative Construction Supply Chain (CSC) risk analysis which is based on a single case study of an Engineering-Procurement-Construction (EPC) contractor mainly active in the Gulf Cooperation Council (GCC) region that focuses on the delay of critical materials. The risk analysis utilized the Bow-Tie model to explore the risks entailed to a construction company originated by basic CSC fault scenarios. The Bow-Tie method consists of two other risk analysis models namely Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). FTA maps the connection of the root causes of a critical event which in our case is the delay of the critical material, while the ETA maps the connection of the latter with its potential outcomes. The basic fault scenarios of the former model and the outcomes of the latter were extracted from semi structured interviews of CSC professionals. Based on those, preventive barriers and recovery measures were suggested by the interviewees that formed the Bow-Tie analysis.

The FTA revealed 37 different basic CSC fault scenarios that can lead to the critical event which were categorized in 5 main CSC processes and 1 more that includes uncertain faults or force majeure. In total, 6 categories were formed namely Management, Planning, Logistics, Manufacturing, Post-delivery and Force Majeure. Out of those CSC fault scenario categories, two were the most common, Management and Planning.

The ETA revealed 5 different possible outcomes of a critical material delay. The significance of the outcome depends on how efficient the recovery mechanisms were after the happening of the critical event. Outcome 1 was the least impactful, involving some minor extra costs, and none to insignificant project delay, going up to outcome 5 which represents the worst-case scenario, involving catastrophic project delay, very high extra costs, contractual issues, and reputational damage to the company.

In the Bow-Tie model, the 5 outcomes that were extracted by the ETA were generalized into 4 different consequences namely Financial Damage, Commercial Implications, Legal Issues, and Decay of People. These 4 consequences represent different business aspects of the construction organization. The Bow-Tie model, as a risk analysis tool, identifies what are the causes that lead to a loss event (critical material delay), what are the measures to prevent this from occurring, how can the effect of it be minimized, and what are the possible consequences of that.

The risk level of the 4 consequences was calculated and the results show that Financial Damage has the highest risk level (Very High Risk) followed by Legal Issues (High), then Commercial Implications (Medium), and lastly Decay of people (Medium). The results of the risk analysis also indicated that, according to the risk level of each of the above-mentioned consequences, measures of different urgency had to be taken into account.

The significance of the results of this research for the CSC professionals is threefold. Firstly, for the CSC professionals to perceive that certain basic CSC faults could potentially lead to serious consequences for the business. Secondly, to unveil the importance of implementing dynamic risk management into the CSC since project plans are constantly changed by the new inputs of the various stakeholders. Lastly, to highlight the value of considering the CSC as a function that has direct effects on the business entity and therefore, CSCRM must consider the consequences that a simple CSC fault may have on the rest of the business functions.

8. Research Limitations and Future Directions

This thesis delved into the CSCRM topic by focusing on the causes and the results that the delay of delivery of a critical material or equipment has to an EPCC as an organization. The research approach of the author to this subject was to gather data by a specific EPCC that is engaged in construction business activities mainly in the GCC region. The nature of this approach is, per se, a research limitation since different conclusions might had been drawn if the investigation included data from more than one EPCCs, or by gathering data from construction organizations that are engaged to construction activities in different regions. Furthermore, the types of projects that were used to describe the process of CSC were strategically chosen since not all types of projects involve the procurement of long lead items. An example of a type of project that does not involve the procurement of long lead items in its scope would be one a civil project for infrastructure works without complicated permanent equipment. Although, the CSC of such projects would also present significant risks related to the continuous flow of raw materials, human resources, construction site space availability, special permits, and more.

Based on this thesis' findings, any researchers that might desire to enrich the CSCRM science are encouraged to investigate the implementation of the CSC to the construction organization, and the reasons why such function is important for it. Moreover, empirically, the comparison of the CSC to the manufacturing industry SC is unfounded, therefore the CSC is a totally different type of SC and that fact serves as a proof that this topic is insufficiently examined.

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Appendix 1

Title	Year	Journal Name	Volume
A comparative study of project risk management with risk breakdown structure (RBS): a case of commercial construction in India	2024	INTERNATIONAL JOURNAL OF CONSTRUCTION MANAGEMENT	24
A Conceptual Development Framework for Prefabricated Construction Supply Chain Management: An Integrated Overview	2020	SUSTAINABILITY	12
A conceptual framework for effective contracting in construction supply chains	2020	International Journal of Construction Supply Chain Management	10
A decision support approach employing the PROMETHEE method and risk factors for critical supply assessment in large-scale projects	2022	Operations Research Perspectives	9
A neo-institutional view of the transaction cost drivers of construction supply chain risk management	2021	Supply Chain Management	26
A novel fuzzy hybrid neutrosophic decision-making approach for the resilient supplier selection problem	2020	International Journal of Intelligent Systems	35
A Structural Equation Model to Analyze the Effects of COVID-19 Pandemic Risks on Project Success: Contractors' Perspectives	2023	ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering	9
A Systematic Approach to Identify and Manage Interface Risks between Project Stakeholders in Construction Projects	2024	CivilEng	5
A systematic review of 'enablers of collaboration' among the participants in construction projects	2021	INTERNATIONAL JOURNAL OF CONSTRUCTION MANAGEMENT	21
Android application prototype for construction logistics tracking	2022	Innovative Infrastructure Solutions	7
Assessment of critical risk and success factors in construction supply chain: a case of Pakistan	2022	International Journal of Construction Management	22
ASSESSMENT OF RISK FACTORS AND PROJECT SUCCESS IN CONSTRUCTION INDUSTRY	2022	TRANSFORMATIONS IN BUSINESS & ECONOMICS	21
Assessment of risks in the purchase process of construction companies	2016	Journal of Chemical and Pharmaceutical Sciences	9
Assessment of visibility in industrial construction projects: a viewpoint from supply chain stakeholders	2021	CONSTRUCTION INNOVATION-ENGLAND	21
BIM contributions to construction supply chain management trends: an exploratory study in Canada	2022	International Journal of Construction Management	22

Blockchain and Smart Contracts: A Solution for Payment Issues in Construction Supply Chains	2021	INFORMATICS-BASEL	8
Blockchain applied to the construction supply chain: A case study with threat model	2020	FRONTIERS OF ENGINEERING MANAGEMENT	7
Blockchain Technology in Construction Supply Chain Management: Enhance Transaction Speed, Cost Effectiveness And Security	2023	Journal of Advanced Research in Applied Sciences and Engineering Technology	32
Collaborative interorganizational relationships in a project-based industry	2021	Buildings	11
Construction supply chain management: A systematic literature review and future development	2023	JOURNAL OF CLEANER PRODUCTION	382
Counterfeiting risk governance in the capital projects supply chain	2015	Journal of Construction Engineering and Management	141
COVID-19 emerging risk assessment for the construction industry of developing countries: evidence from Iraq	2024	International Journal of Construction Management	24
Curing congenital construction industry disorders through relationally integrated supply chains	2003	Building and Environment	38
Current practices and insights on supply chain risk management in the construction industry: A review	2020	International Journal of Supply Chain Management	9
Defining Supply Chain Visibility for Industrial Construction Projects	2021	FRONTIERS IN BUILT ENVIRONMENT	7
Developing a sustainable forward supply chain configuration for construction industry under uncertainty condition: a case study	2024	CLEAN TECHNOLOGIES AND ENVIRONMENTAL POLICY	26
Digital twin for supply chain coordination in modular construction	2021	Applied Sciences (Switzerland)	11
Evaluating the modus operandi of construction supply chains using organisation control theory	2015	International Journal of Construction Supply Chain Management	5
Exploring Implementation of Blockchain for the Supply Chain Resilience and Sustainability of the Construction Industry in Saudi Arabia	2022	Sustainability (Switzerland)	14
Factors affecting the cooperative relationships in material supply chain of construction enterprises	2024	Organization, Technology and Management in Construction	16
How Far Can BIM Reduce Information Asymmetry in the Australian Construction Context?	2015	PROJECT MANAGEMENT JOURNAL	46
Hybrid intelligent vehicle system for managing construction supply chain in	2020	World Journal of Engineering	18

precast concrete building construction projects			
Identification and assessment of risks related to digitalization in Indian construction: a quantitative approach	2023	BUSINESS PROCESS MANAGEMENT JOURNAL	29
Identifying issues in adoption of AI practices in construction supply chains: towards managing sustainability	2023	Operations Management Research	16
Identifying supply chain capabilities of construction firms in industrialized construction	2021	Production Planning and Control	32
Impact of covid-19 on supply chain management in construction industry in Kashmir	2023	Asian Journal of Civil Engineering	24
Impact of the Coronavirus disease 2019 and the post-pandemic construction sector (Pakistan)	2022	International Journal of Managing Projects in Business	15
Industry 4.0 and supply chain process re-engineering A coproduction study of materials management in construction	2020	BUSINESS PROCESS MANAGEMENT JOURNAL	26
Information modelling for a construction project risk management system	2000	Engineering, Construction and Architectural Management	7
Integrated supplier selection framework in a resilient construction supply chain: An approach via analytic hierarchy process (AHP) and grey relational analysis (GRA)	2017	Sustainability (Switzerland)	9
Integrating BIM and Blockchain across construction lifecycle and supply chains	2023	Computers in Industry	148
INTERNATIONAL JOINT VENTURE BETWEEN ASEAN AND GULF: BIDDING AND DELIVERING BAHRAIN INTERNATIONAL FORMULA-1 CIRCUIT	2014	TRAMES-JOURNAL OF THE HUMANITIES AND SOCIAL SCIENCES	18
Key risks in the supply chain of large scale engineering and construction projects	2018	Supply Chain Management	23
Linking supply chain disruptions with organisational performance of construction firms: the moderating role of innovation	2021	JOURNAL OF FINANCIAL MANAGEMENT OF PROPERTY AND CONSTRUCTION	26
Logistics simulation modelling across construction supply chains	2011	Construction Innovation	11
Managerial framework for quality assurance of cross-border construction logistics and supply chain during pandemic and post-pandemic: lessons from COVID-19 in the world's factory	2024	ENGINEERING CONSTRUCTION AND ARCHITECTURAL MANAGEMENT	
Managing stakeholder-associated risks and their interactions in the life cycle	2021	JOURNAL OF CLEANER PRODUCTION	323

of prefabricated building projects: A social network analysis approach			
Multi-constraint information management and visualisation for collaborative planning and control in construction	2003	Electronic Journal of Information Technology in Construction	8
Multi-objective optimization for improved project management: Current status and future directions	2022	Automation in Construction	139
Optimization strategies to eliminate interface conflicts in complex supply chains of construction projects	2017	Journal of Civil Engineering and Management	23
Performance assessment on the application of artificial intelligence to sustainable supply chain management in the construction material industry	2021	Sustainability (Switzerland)	13
Performance measurement of construction suppliers under localization, agility, and digitalization criteria: Fuzzy Ordinal Priority Approach	2022	ENVIRONMENT DEVELOPMENT AND SUSTAINABILITY	
Prefabricated Construction Risks: A Holistic Exploration through Advanced Bibliometric Tool and Content Analysis	2023	Sustainability (Switzerland)	15
Prioritization of interdependent uncertainties in projects	2020	INTERNATIONAL JOURNAL OF MANAGING PROJECTS IN BUSINESS	13
Project Complexity and Risk Management (ProCRiM): Towards modelling project complexity driven risk paths in construction projects	2016	INTERNATIONAL JOURNAL OF PROJECT MANAGEMENT	34
Re-engineering a construction supply chain: A material flow control approach	2003	Supply Chain Management	8
Relationship quality in construction projects: A subcontractor perspective of principal contractor relationships	2021	International Journal of Project Management	39
Resilient Capabilities to Tackle Supply Chain Risks: Managing Integration Complexities in Construction Projects	2022	Buildings	12
Review of supply chain management within project management	2021	Project Leadership and Society	2
Risk Assessment in the Industry Chain of Industrialized Construction: A Chinese Case Study	2022	BUILDINGS	12
Risk assessment model selection in construction industry	2011	EXPERT SYSTEMS WITH APPLICATIONS	38
Risks and performance in supply chain: the push effect	2018	International Journal of Production Research	56
Risks and supply chain performance: globalization and COVID-19 perspectives	2023	International Journal of Productivity and Performance Management	72

Service-oriented supply chain: what do we know about its risks?	2024	INTERNATIONAL JOURNAL OF LOGISTICS-RESEARCH AND APPLICATIONS	
Simulating the impact of supply chain management practice on the performance of medium-sized building projects	2010	Construction Management and Economics	28
Supply chain management: A review of implementation risks in the construction industry	2012	Business Process Management Journal	18
Supply Chain Risk Assessment and Mitigation Approaches for Small-Sized Road Construction Projects	2021	ENGINEER-JOURNAL OF THE INSTITUTION OF ENGINEERS SRI LANKA	54
Supply chain risk assessment in disruptive times: opportunities and challenges	2023	JOURNAL OF ENTERPRISE INFORMATION MANAGEMENT	36
Supply chains in the construction industry	2010	Supply Chain Management: An International Journal	15
The disruptive factors and longevity effects of Covid-19 and Brexit on the SMEs construction supply chain in the UK	2024	JOURNAL OF FINANCIAL MANAGEMENT OF PROPERTY AND CONSTRUCTION	29
The dynamics of vulnerabilities and capabilities in improving resilience within Malaysian construction supply chain	2018	Construction Innovation	18
The effect of relationship management on project performance in construction	2012	International Journal of Project Management	30
The impact of alternative financial supply chain management practices on supply risk: A relationship quality and buyer relative power perspective	2022	INDUSTRIAL MARKETING MANAGEMENT	100
The impact of supply chain innovation on competitive advantage in the construction industry: Evidence from a moderated multi-mediation model	2021	Technological Forecasting and Social Change	162
The impacts of operational risks in the supply chain of construction projects in malaysia	2020	Tehnicki Vjesnik	27
The Relationship among Team Skills and Competencies, Construction Risk Management and Supply Chain Performance with Moderating Effect of Government Laws Acts, and Policies: A Study from Iraq Construction Contractors	2022	International Journal of Construction Supply Chain Management	12
The role of collaboration and integration in the supply chain of construction industry	2020	Civil Engineering Journal (Iran)	6
The Status of the Saudi Construction Industry during the COVID-19 Pandemic	2023	SUSTAINABILITY	15
Towards an agent-based construction supply network modelling and simulation platform	2005	Automation in Construction	14

Transformer-Based Named Entity Recognition in Construction Supply Chain Risk Management in Australia	2024	IEEE Access	12
Underlying causes and mitigation measures of delays in construction projects An empirical study	2020	JOURNAL OF FINANCIAL MANAGEMENT OF PROPERTY AND CONSTRUCTION	25