Risk-Based Decision Support Framework for Managing Excessive Geometric Variability Issues in Modular Construction

By

Mohammed S. A. Enshassi

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Examining Committee Membership

The following individuals served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner	**NAME**	**:**	Saiedeh Razavi
	Title	**:**	Associate Professor, Civil Engineering McMaster University
Supervisors	**NAME**	**:**	Scott Walbridge
	Title	**:**	Associate Professor, Civil and Environmental University of Waterloo
	NAME	**:**	Jeffrey West
	Title	**:**	Adjunct Professor, Civil and Environmental University of Waterloo
Internal Member	**NAME**	**:**	John Straube
	Title	**:**	Professor, Civil and Environmental Engineering University of Waterloo
	NAME	**:**	Tarek Hegazy
	Title	**:**	Professor, Civil and Environmental Engineering University of Waterloo
Internal-External Member	**NAME**	**:**	Jonathan Enns
	Title	**:**	Assistant Professor, Architecture University of Waterloo

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Managing and controlling excessive dimensional and geometrical variability (i.e., tolerances) of modular components and assemblies during the fabrication, transportation, and erection phases, represents a major issue in modular construction (MC) projects. The current industry practices manage tolerance-related risks either reactively (e.g., onsite adjustment by applying forces, shimming, and replacing defected components), or proactively (e.g., 2D & 3D jigs, prototyping (mock-ups), and 3D laser scanning technology, and tolerance theory). The reactive approaches include expensive and time-consuming field rework, schedule delays, and serviceability or functional failures. On the other hand, the proactive approaches require a significant amount of investment (resources) during early project phases (design and fabrication) to produce modular systems that are compliant with design specifications. Thus, improper assessment and reactive management of excessive geometric variabilities due to out-of-tolerances can result in extensive site-fit rework, cost overruns, schedule delays, quality issues, and owner dissatisfaction.

The perceived risks and challenges will continue to fuel the reluctance of industry practitioners to apply modularization in future construction projects. Therefore, different decision support systems (DSSs), frameworks, decision matrices, models, and toolkits have been developed to evaluate modularization feasibility (benefits and challenges) for construction projects during early project phases. However, these DSSs, frameworks, and toolkits are not without their limitations. Most previously developed DSSs and toolkits focus on: 1) strategic and high-level decisions; 2) general modularization risks ; and 3) reactive solutions. Also, these DSSs and toolkits lack: 1) quantitative and probabilistic risk assessment techniques to evaluate the modularization risk impact on the overall project performance (cost, schedule, quality, etc.); 2) consideration of the impact of the unique relationships (propagation behaviour and cause-effect relationship) among risks in decision making process; and 3) integration of dynamic risk assessment and management techniques to revise the risk management plans as more accurate modularization process capability information becomes available. With this in mind, further efforts are needed to systematically evaluate tolerance-related risks and excessive geometric variability issues, and proactively manage their impact, both of which are expected to improve modularization performance and maximize its benefits in construction projects.

The goals of the research presented in this research are to develop: 1) a systematic process to identify, quantitatively evaluate, and proactively manage tolerance-related risks by identifying optimum geometric variability (using a strict or relaxed tolerance approach) that will achieve cost efficiency requirements; 2) an efficient approach to thoroughly evaluate and manage tolerance-related risks at local and global levels by incorporating the propagation behaviour and cause-effect relationships among risks in the decision making process; and 3) a dynamic methodology to continually evaluate tolerance-based risk management plans and revise risk response decisions as new information becomes available.

The results of the work conducted for this research study contribute to both knowledge and practice. On the knowledge side, the main contribution is the introduction of an efficient risk management methodology, which will support modularization decision-making process with respect to the selection of optimum approaches to proactively manage tolerance-related risks and excessive geometric variability issues in construction projects. On the practice side, this research will enhance in a quantitative and proactive manner our understanding of the unique risks and challenges associated with MC, which will help the stakeholders, including project risk managers, decision makers, and construction managers, to improve modularization performance and maximize its benefits.

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List of Abbreviations

ACI : American Concrete Institute
A-D : Anderson-Darling
AE : Aggregated Exposure
AEC : Architecture, Engineering and Construction
AFT : Appearance-based Functional Tolerances
AHP : Analytic Hierarchy Process
AISC : American Institute of Steel Construction
BDB : Bid-Design-Build
BIM : Building Information Modelling
BSI : British Standard Institute
BSS : Build System Selection
CCM : Cause Comparison Matric
CDF : Cumulative Distribution Function
CGD : Current Geometric Discrepancy
CII : Construction Industry Institute
COAA : Construction Owner Association of Alberta
CSA : Canadian Standard Association
DB : Design-Build
DBB : Design-Bid-Build
DC : Direct Cost
DfPA : Design for Parallel Assembly
DRA : Dynamic Risk Assessment
DSM : Design Structure Matrix
DSS : Decision Support System
EC : Equipment Cost
ECM : Effect Comparison Matric
EGD : Expected Geometric Discrepancy
EPC : Engineering, Procurement, and Construction
ET : Essential Tolerances
FEP : Front End Planning
FFT : Fit-up Functional Tolerances
FT : Functional Tolerances
GE : Global Exposure
IBS : Industrialized Building Selection
IM : Interface Management
IMMPREST : Interactive Model for Measuring Preassembly and Standardization
IPD : Integrated Project Delivery
IPRA : Integrated Project Risk Assessment

K-S	:	Kolmogorov-Samirnov
LE	:	Local Exposure
MC	:	Modular Construction
MCS	:	Monte Carlo Simulations
MEP	:	Mechanical, Electrical, and Plumbing
MMC	:	Modern Methods of Construction
MODEX	:	Modularization Expert
MS	:	Mitigation Strategy
NCM	:	Numerical Cause Matrix
NCV	:	Numerical Cause Vector
NDSM	:	Numerical Design Structure Matrix
NEM	:	Numerical Effect Matrix
NEV	:	Numerical Effect Vector
PDF	:	Probability Density Function
PERT	:	Program Evaluation and Review Technique
P-I	:	Probability-Impact
PM	:	Project Manager
PMI	:	Project Management Institute
PPMOF	:	Prefabrication, Preassembly, Modularization, and Offsite Fabrication
PPP	:	Public-Private Partnership
QRA	:	Quantitative Risk Assessment
RB	:	Relocatable Building
RICC	:	Rogers Intelligent Capacity Centre
RMF	:	Risk Management Framework
SME	:	Subject Matter Expert
T/H/E	:	Transportation, Handling, and Erection
TIC	:	Total Installed Cost

Chapter 1

Introduction

1.1 Background

The construction industry is usually subjected to criticism because of cost overruns, schedule delays, low productivity rates, ineffective quality management systems, safety issues, and inefficient production processes (Gibb, A., 2001; Jonsson & Rudberg, 2014; Lawson et al., 2011; Mao et al., 2013). Therefore, recent years have seen a growing interest by the architecture, engineering, and construction (AEC) industry to develop innovative design solutions and efficient construction methods with the aim of improving the overall performance of construction projects (CII, 2011b; Smith, 2011).

The AEC industry has adopted modern methods of construction, such as modular construction (MC) and offsite fabrication techniques, by learning from other sectors such as manufacturing, nuclear, and shipbuilding (Egan, 1998; Pan et al., 2005; Ross et al., 2006). In modular construction, most of the construction work-activities are performed in a controlled environment by producing modular components and assemblies at offsite fabrication facilities, which are then transported to the job site for final assembly and alignment. Solving the problems that have arisen with the transition from onsite to offsite construction has required a great deal of research effort dedicated to the investigation and evaluation of needs, potential advantages and disadvantages, constraints and barriers, applications, etc. Many studies have confirmed the potential benefits of employing MC as a building method in improving the performance of construction projects by reducing total installed cost (Chiang et al., 2006; Gibb & Isack, 2003; Love et al., 2016), improving schedule performance (Lopez-Mesa et al., 2009; Pons & Wadel, 2011), reducing labour demand (Ghodrati et al., 2018; Nadim & Goulding, 2010), improving quality control (Jaillon & Poon, 2008; Li et al., 2018; Lu et al., 2013; O’Connor et al., 2015a), decreasing construction waste (Baldwin et al., 2009; Tam et al., 2006; Tam et al., 2007), and reducing resource depletion (Aye et al., 2012; Won et al., 2013). Despite the well documented benefits that can be derived from modularization, the engineering, procurement, and construction (EPC) industry is still struggling to achieve the high-levels of modularization seen in other sectors such as manufacturing, nuclear, aerospace, and shipbuilding (CII, 2011a; O'Connor, J. T. et al., 2013; Pasquire et al., 2004). Modularization's broad application and adoption is challenged by industry-wide barriers and risks, which include high initial cost (Jaillon & Poon, 2009; Lovell & Smith, 2010), lack of accurate quality control systems (Kamar et al., 2009), lack of design codes and standards (Goodier & Gibb, 2005a; Kamar et al., 2009; O'Connor et al., 2015b), lack of capable contractors (Blismas et al., 2005; Lovell et al., 2010), lead-in time during the engineering and design phase (CII, 2002), and complex logistics (Naqvi et al., 2014a).

Out-of-tolerance and out-of-alignment issues represent a key risk factor for the hesitancy among the main project parties to adopt modularization as a building method (Milberg, 2006; Milberg et al., 2002). Excessive geometric variabilities in modular components and assemblies arise from various sources including equipment deficiencies, human errors, fabrication and assembly process limitations, quality control tool imprecision, and damage during transportation (Choi et al., 2016; Gibb, 1999; Gibb, A. G., 2001; Lawson & Richards, 2010; Pan et al., 2007). The improper assessment and reactive management of such risks can result in extensive site-fit rework, cost overruns, schedule delays, quality issues, and owner dissatisfaction (Ballast, 2007; Gibb, 1999; Pasquire et al., 2004).

The perceived risks and challenges will continue to fuel the reluctance of industry practitioners to apply modularization in future construction projects. Therefore, a variety of decision support systems (DSSs), frameworks, decision matrices, models, and toolkits have been developed to evaluate modularization feasibility (benefits and challenges) for construction projects during early project phases. Such DSSs and tools will support modularization decision makers either in making: 1) strategic and high-level decisions about whether to apply stick-built or modular construction methods, or 2) tactical decisions to maximize project performance and benefits. The application of strategic-based DSSs, such as *PPMOF* (CII, 2002; Song et al., 2005), *IMMPREST* (Pasquire et al., 2005), and the *Modularization Business Case Analysis Tool* (Choi & O'Connor, 2015), is helpful in enabling high-level decisions on whether a project can lend itself best to stick-built or modular construction (or some combination thereof) to achieve the overall objectives (cost, schedule, quality, safety, etc.). On the other hand, tactical DSSs such as the *Tolerance Management Tool* (Milberg, 2006) support industry practitioners by increasing their chances of success in implementing modularization if it is the right strategy. Although the tool (or the five-step methodology) developed by Milberg (2006) explicitly focuses on identifying tolerance failure modes and managing their impact by resolving the mismatch between desired tolerances and process capabilities, it focuses on the “strict and tight” tolerance notion to build modular systems and on design-based mitigating strategies (i.e., does not consider fabrication, transportation, and erection mitigation strategies). In the strict tolerance approach, the modules will be designed and built to be within strict tolerance limits through all of the project phases. Using the strict approach (i.e., tolerance values dictated from standards) might: 1) reduce the amount of rework required to adjust the module geometry onsite, 2) increase the opportunity of building 100% modularized units, and 3) speed up construction (alignment) time during the erection phase. However, the strict tolerance approach requires a high investment (time and money) in the planning phase to anticipate and solve tolerance issues, and in the fabrication phase to buy the assembly tools, jigs, and equipment needed to achieve the strict tolerances. Therefore, a relaxed tolerance approach could be considered as an alternative to the strict approach. The relaxed tolerance approach focuses on designing and building modules that will accommodate geometric discrepancies by using, for example, adjustable or bolted connections. The module geometry is expected to exceed the strict tolerance limits, but without exposing the structure to high risk due to dynamic loads (i.e., transportation, handling, and erection loads). The relaxed tolerance approach is therefore considered as a spectrum/continuum of dimensional and geometric values that are greater than the strict tolerance values and lower than the limit for structural failure. The relaxed tolerance approach might reduce fabrication cost (i.e., no need to use precise quality control systems such as 3D imaging or jigs) and reduce rework cost at the job site compared to the strict approach (i.e., the modules will be designed to be easily/quickly fixed and adjusted). However, this approach may necessitate a reduction in modularization scope/extent to protect non-structural components (e.g., brittle materials such as windows, doors, drywall, etc. must be installed onsite). The *Tolerance Management Tool* (Milberg, 2006) also does not include a systematic process for quantitatively evaluating a tolerance failure modes' impact on overall project objectives (cost, schedule, quality, etc.), and lacks a practical approach for optimizing the risk response decisions.

On the other hand, different risk assessment frameworks and risk management toolkits have been developed for assisting industry practitioners to systematically assess modularization risks and challenges during early project phases. Li et al. (2013) introduced a framework for evaluating the risks of modular and offsite fabrication in a quantitative manner and probabilistic fashion, using a Fuzzy AHP (analytical hierarchy process) technique. However, the application of this framework has a limited scope, since it focuses only on risk assessment rather than integrating both risk assessment and risk management techniques into the developed framework to support decision making. This framework also focuses on evaluating risks independently and individually (i.e., the relationships among risks are not considered in the risk assessment process). Moreover, the presented risk assessment process of this framework is designed to be performed on a static basis during early project phases. On the other hand, the Construction Industry Institute (CII) (2013a, 2013b) developed an integrated project risk assessment (*IPRA*) toolkit for probabilistic risk evaluation in construction projects. While *IPRA* provides a detailed methodology for analyzing risks at three levels (identification, deterministic, and probabilistic), it still lacks a practical process for identifying and evaluating the unique relationships among risks (cause-effect relationships and propagation behaviour), and lacks a practical methodology for optimizing risk management plans. Moreover, it evaluates and manages the risks on a static basis (i.e., it does not include a methodology for updating the input information of main risk characteristics when more realistic data become available). Therefore, it is believed that further improvement is needed to develop a methodology for proactive, thorough, and dynamic management of tolerance-related risks and excessive geometric variability issues, which will support the modularization decision making process with respect to the optimum selection of mitigation strategies, in order to improve modularization performance and maximize its benefits.

1.2 Research Motivation

Efficient evaluation and proactive management of tolerance-related risks and excessive geometric variability issues can improve modularization performance and maximize its benefits. However, a review of the literature conducted for this research has uncovered the following deficiencies:

- Most previously developed modularization DSSs and toolkits focus on:
    1) strategic and high-level decisions (i.e., whether to apply stick-built or modular construction, but not identifying best approaches for implementation if modularization is the right strategy),
    2) general modularization risks (e.g., market demand, environmental impact, social and political conditions, labour rates/availability/skills, material supply chain, etc.),
    3) the strict and tight tolerance approach, and
    4) reactive solutions and stick-built management approaches.
- Most previously developed modularization risk assessment frameworks and risk management toolkits lack:
    1) quantitative and probabilistic risk assessment techniques to evaluate the impact of the risks associated with modularization on the overall project performance (cost, schedule, quality, etc.),
    2) consideration of the impact of the unique relationships (propagation behaviour and cause-effect relationship) among tolerance-related risks in the decision making process, and
    3) integration of dynamic risk assessment and management techniques to revise the risk management plans when more accurate modularization process capability data is available.

1.3 Research Objectives

The objectives of this research are as follow:

1) to develop a systematic methodology for the proactive management of tolerance-related risks by identifying optimum geometric variability using a strict or relaxed tolerance approach,
2) to develop a framework for the thorough quantitative evaluation and management of excessive geometric variability issues and their unique relationships at local and global levels, and
3) to develop a methodology for the dynamic assessment and proactive management of tolerance-related risks and excessive geometric variability issues.

1.4 Methodology

This section outlines the methods and techniques to be used for achieving the research objectives identified in the previous section.

To better understand the state-of-the-art in research on means for improving the performance of modular construction (MC) projects, a literature review was first performed in the following areas: definition and levels of modularization, construction tolerances, risks associated with modularization, current industry practices and standards to proactively manage modularization risks, and modularization DSSs and toolkits to support decision-making. The literature review includes studies on industry practice and academic knowledge.

Three different risk management frameworks and methodologies presented are then developed based on a synthesis of the obtained data from the industry partner for a case study project (e.g., risk management methodology and lessons learned documents), along with a review of best practices utilized in other industries, such as the manufacturing, shipbuilding, nuclear, and oil and gas sectors. The newly developed frameworks and methodologies include 1) a systematic process for identifying the optimum geometric variability using either strict or relaxed tolerance approach; 2) an efficient approach for thoroughly evaluating and managing tolerance-related risks at both local and global levels by employing existing methods including a probability-impact (P-I) risk model, a design structure matrix (DSM), and an analytical hierarchy process (AHP); and 3) a dynamic methodology for continually evaluating tolerance-based risk management plans and revising risk response decisions using Bayesian theory.

The developed risk management frameworks and methodologies were then demonstrated a case project (two identical modular data centre projects), with the input from the fabrication team (project manager, modular designers, director of risk control, plant manager, and project lead foreman) and the erection team (site manager and superintendents). Site visits were also conducted to the shop during the fabrication and assembly processes, and to the project site during the module fit-up and alignment phases of the project.

1.5 Scope of thesis

For the current research project, an intensive review of the existing literature has been conducted in order to identify appropriate boundaries of the work under consideration. Based on this review, the focus of the presented research is as follows:

- volumetric modules with high modularization percentage,
- unique risks to modularization (i.e., tolerance-related risks and excessive geometric variability issues),
- proactive and tolerance-based mitigation strategies, considering all of the phases of a modular construction project (e.g., design, fabrication, transportation, and erection), and
- the application of modularization concepts in building (e.g., commercial and residential) construction projects.

1.6 Thesis Organization

The thesis is organized into six chapters. The content of the chapters is as follows:

Chapter 1: (the current chapter) introduces the context of the study, presents the objectives and scope, outlines the research methodology, and presents the thesis structure.

Chapter 2: provides an overview of the current definitions, levels, advantages and disadvantages, and risks and challenges associated with modular construction. The tolerance definitions and current approaches employed for managing tolerance-related risks (excessive geometric variability issues) in modular construction project are summarized in this chapter. Also, it explores the current DSSs and risk management frameworks that have been developed to support modularization decision making process with respect to the selection of optimum mitigation strategies. Finally, current risk assessment and management approaches in the construction industry are reviewed.

Chapter 3: presents the proposed framework for identifying the optimum geometric variabilities (i.e., tolerances) using either strict or relaxed tolerance approach.

Chapter 4: introduces the proposed framework for thoroughly evaluating and managing the tolerance-related risks at both local and global levels using existing methods including a probability-impact (P-I) risk model, a design structure matrix (DSM), and an analytical hierarchy process (AHP).

Chapter 5: presents the proposed methodology for dynamic assessment and proactive management of tolerance-related risks and excessive geometric variability issues using Bayesian theory.

Chapter 6: summarizes the main lessons learned in the development of the presented methodologies and the conclusions drawn from their implementation on a case study project. Contributions to the existing body of knowledge are also identified. Limitations are discussed, and potential research avenues for future work are recommended.

Chapter 2

Literature Review

2.1 Summary

This chapter starts with a thorough review of the literature related to the main areas of modular construction (MC): definitions, types of modular systems, development of MC and offsite fabrication concepts in construction industry, and risks of MC. Tolerance level and definitions introduced as well as current approaches to manage tolerance-related risks are summarized. Decision support tools relevant to MC are presented, and pertinent knowledge gaps are identified. In the final section, the definitions of risk and uncertainty, risk modelling and management techniques are presented.

2.2 Definitions of Modular Construction and Offsite Fabrication

The literature offers a variety of terms for describing MC concept: in the UK, it is referred to as the modern method of construction (MMC) (Pan et al., 2007); in the United States, it is called prefabrication, preassembly, modularization, and offsite fabrication (PPMOF) (Song et al., 2005; Tatum et al., 1987); in Japan and China, the term is prefabricated house building (Barlow & Ozaki, 2005; Jaillon et al., 2009); and in Sweden, the term is industrialized house-building (Lessing et al., 2015b). In general, most of these descriptions cover the same technological concepts.

Although many of the terms that include “offsite” in the name are still in use, offsite and MMC have become expressions employed for identifying the two main schools of thought (Pan et al., 2012) and are now regarded as two "banners" under which improvements in efficiency and quality through offsite technologies can be categorized. The current industry practices often use these two concepts interchangeably (Elnaas et al., 2009) in spite of the fact that they are actually distinct. Gibb and Pendlebury (2006) defined offsite as a process involving manufacturing that takes place away from the site followed by the installation of the manufactured assemblies onsite. Although many offsite techniques are not in fact “modern” but have been used for decades, all offsite methods may be regarded as falling within a generic MMC heading, but not all MMC techniques can be called offsite (Kamar et al., 2011; Lusby-Taylor et al., 2004; O'Neill & Organ, 2016; Pan et al., 2008; Taylor, 2010). Offsite thus represents a primary and important subset of the broader MMC family. Despite these differences, however, both offsite and MMC refer to a combination of people, processes, and product and overlooking any of these three elements jeopardizes the realization of the potential benefits associated with these construction methods.

Modular construction (MC), which has been chosen as the preferred term for use in this research, can be defined as volumetric units or modules that form a whole building or part of it. Most of these modules are fabricated predominantly offsite in a controlled environment, leaving some work to be performed onsite, such as connections with the foundation, adjacent modules, main drainage and mechanical, electrical, and plumbing (MEP) systems. In this research, the term “modular construction” is used for describing such a system.

2.3 Types of Modular and Offsite Fabrication Systems

Modular construction and offsite fabrication systems comprise a variety of types (Figure 2.1):

Components and Subassembly: This category refers to small elements and subassemblies that are assembled prior to installation, such as doors and windows frames, door hardware, and MEP systems.

Panelized Systems: Flat panel units, such as wall, floor, and roof panels, are built offsite and then transported to be assembled onsite to create a 3D structure that will form the complete building (Fawcett, Allison et al. 2005). The panels could be open (bare frame) or closed (bare frame with window/door frames and drywall installed) (Ross et al., 2006).

Modular Systems: These systems are composed of volumetric modules that form either part of a building or an entire building, with most being built primarily offsite, leaving only a small amount of work to be completed onsite.

Hybrid Construction Systems: Also called semi-volumetric construction, this term refers to a combination of volumetric modules and panelized systems. In these systems, volumetric modules, such as kitchen/bathroom pods, are used as part of the building structure, and panelized systems are employed in the remainder of the building (Ross et al., 2006).

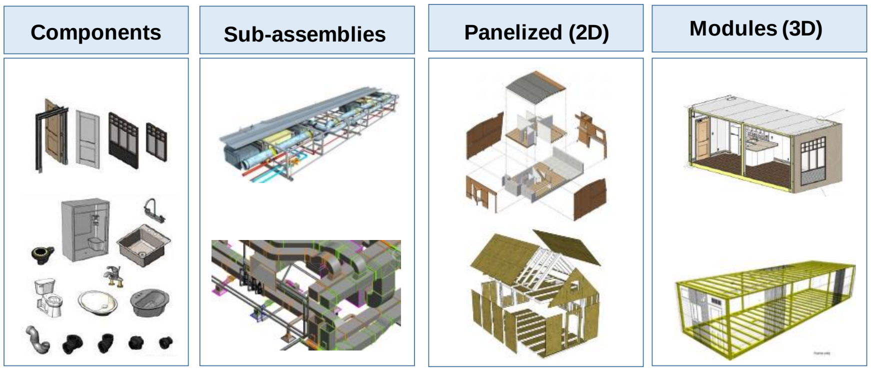


Figure 2.1 Types of modular and offsite fabrication systems.

2.4 Development of Modular and Offsite Fabrication Concepts for Construction Projects

This section reviews the development of the modular and offsite fabrication concepts in the construction industry. The review is limited application of MC in commercial and residential sectors.

2.4.1 Historical Background

Onsite techniques have traditionally been used in most construction projects, which are often subject to schedule delays and cost overruns. The onsite building process entails numerous unforeseen challenges, such as the effects of inclement weather, low labour productivity, and substandard materials, all of which can affect the completion and performance of the project. The introduction of MC and offsite fabrication concepts as a means of solving onsite problems is not new to the construction industry.

After both World War I and World War II, the many demolished houses, the lack of new construction techniques, and deficient maintenance resulting from labour shortages, all drove a compelling need for new construction methods (Ross et al., 2006). Under continual pressure from a growing population and an expanded demand for housing, governments offered additional financial support for the development of modern, new construction methods

(Marshall et al., 2013). For example, the Swedish government made the biggest state investment in housing through the million homes programme. The aim was to construct a million new dwellings during the programme's ten-year period (1965 – 1975) (Hall & Vidén, 2005). At the time, the million homes programme was the most ambitious building program in the world to build one million new homes in a nation with a population of eight million. A variety of offsite fabrication systems were offered: precast concrete, cladding, and steel/timber frames and walls (Lessing et al., 2015c; Venables et al., 2004). The application of offsite fabrication methods in the million homes program were however perceived as creating lower-quality products than onsite methods due to maintenance and repair issues resulting from poor design, lack of fabrication standards, the unavailability of skilled labour, and flawed onsite installation techniques (Bottom, 1996; Lessing et al., 2015b; Nadim & Goulding, 2011).

The reputations of both offsite fabrication and MC have recently changed, and these technologies have become recognized as methods that can improve quality, safety, and productivity while also reducing project durations and cost overruns (Barker, 2004; Pan & Arif, 2011a; Pan et al., 2007). The uptake of the offsite fabrication and modular construction techniques has been attributed to the significant developments took place in component-based systems (e. g. timber frames, roof trusses, steel lintels, etc.) (Pan et al., 2007; Pan et al., 2008). However, despite the professed advantages of using modular and offsite fabrication techniques, their widespread application is still in the early stages of convincing owners and stakeholders to use these methods rather than traditional, onsite construction (MBI, 2015).

2.4.2 Modular Methods in the Construction and Automobile Manufacturing Industries

The trend toward the application of factory mass production and factory-based manufacturing techniques is much better established in the automobile industry than in the construction industry (Figure 2.2). Automakers base their production of car models on a mass-production philosophy that minimizes product diversity and keeps costs low. By decreasing unnecessary complexities in product design and manufacturing processes, Toyota was able to standardize their product components in order to mass produce their automobiles (Cusumano, 1988). Increasing the flexibility of the production and assembly lines increased the number of options available to customers and enabled them to offer a greater variety of car models (MacDuffie et al., 1996). If the mass production principles and the technology associated with manufacturing cars were mimicked in construction projects, production and labour productivity would increase along with the quality of the final product (Alazzaz & Whyte, 2015; Vale, 2003).

Figure 2.2. Modular concept in Manufacturing, Automotive, Aerospace, and Shipbuilding sectors.

The goal of learning from manufacturing processes, especially in the automobile industry, is to develop production techniques for building high-quality long-lasting houses while reducing the total cost. As an example, Toyota not only produces cars but, based on its understanding of the mass-production philosophy in the car industry, has also successfully translated principles derived from manufacturing cars to the construction industry in order to build high-quality, customized, affordable factory-based houses. Their home construction relies on the "Skeleton & Infill" approach (Figure 2.3): flexible infill (i.e., modules built offsite) combined with a long-lasting skeleton structure (Cao et al., 2015; Toyota, 2006; Yingbo et al., 2009).

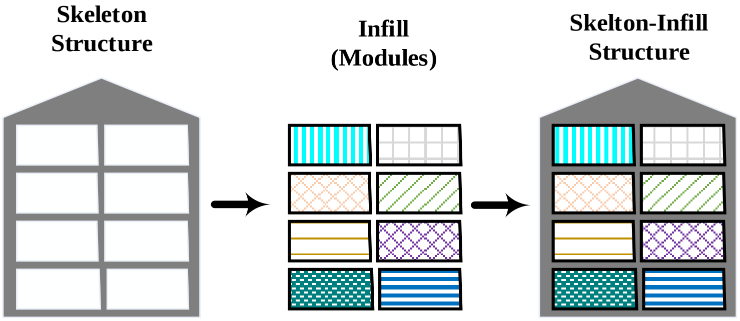


Figure 2.3. Skeleton-Infill housing system.

Another example of the use of modular and offsite fabrication concepts can be seen in IKEA, a Swedish company considered the largest in the world for the sale of housing interiors and furniture (Lessing & Brege, 2015a). Based on a “ready-to-be-assembled” concept, IKEA developed new design options, new fabrication methods, and new materials in order to produce ideal products that are perfectly fabricated offsite in a factory, ready to be assembled onsite in homes, offices, hotels, restaurants, etc. IKEA and Skanska (Construction Company) are collaboratively acquired “new” prefab housing company called BoKlok. Experts from IKEA and Skanska were involved in the design process in order to build high-quality homes with an affordable fixed price. The variety of design options (i.e., module dimensions, limitedness to timber material to build modules structure) are limited to one or two which will make it difficult to satisfy all the customer’s needs. On the other hand, with the limited design lines / options, the fabrication company was able to standardize most of their processes resulting in more cost efficiency (Lessing et al., 2015b).

As a unique, diverse, and project-based industry (Ozorhon et al., 2013), construction involves numerous types of projects, each with its individual characteristics, goals, and stakeholders. Applying modular and offsite fabrication concepts in such an environment requires the involvement of key project parties who must understand the essentials of modular construction processes and how they can cost-effectively enhance the quality of housing construction. Treating the construction of houses and apartment / condo units as if they were car chassis to be built offsite in a factory requires that standardized components (connections, materials, equipment, etc.) be developed and incorporated in a manner that will achieve the same benefits that have accrued in the automotive industry (Vale, 2003).

2.5 Current State of Modular Construction

The construction industry is continually under pressure to apply concepts and techniques from other industries (Gibb, A., 2001). Construction industry practitioners, governments, and clients have been working on the adoption of MC and offsite concepts, addressing concerns about their implementation and attempting to transform a stick-built culture into one that supports the construction of low-cost, high-quality projects.

Regardless of the wealth of knowledge about MC and offsite fabrication concepts, actual application is still limited and below the level expected for commercial and residential projects (Goulding & Arif, 2013; Goulding et al., 2015; Zhai et al., 2014) because majority of industry practitioners are more familiar with onsite and traditional construction techniques than with modular and modern methods (Pan et al., 2007). This section highlights the advantages and challenges of applying MC technologies in construction projects to the potential increase to the take-up in the future.

2.5.1 Advantages of Modular Construction

Numerous studies have revealed the of benefits associated with implementing modularization concept in construction projects. Some of the main benefits can be summarized as follows:

Schedule: One of the most substantial benefits of using modularization concept in the construction industry is the time saved due to early completion. Since the production of the modules in the factory occurs simultaneously with site work, modular buildings can often be constructed faster than ones built completely onsite (Choi & Song, 2014; CII, 2011a; Haas et al., 2000; Larsson & Simonsson, 2012; Zhengdao et al., 2014). Modular building facilities allow workers and construction crews to operate year-round so that modules can be completed quickly with no delays due to inclement weather (Jaillon, 2009; Jaillon et al., 2009; Lu, 2007; Zhang & Skitmore, 2012). This feature makes modular construction suitable for owners who require buildings finished quickly to satisfy completion dates for either occupancy or weather restrictions (MBI, 2015).

Cost: The construction industry is known for having strict profit margins (CII, 2011a; Haas et al., 2000; Kozlovská et al., 2014; Larsson et al., 2012; Lawson et al., 2012). Even if it creates only a small cost reduction, the use of modular construction could have a significant impact on the performance of a construction firm. Most cost savings are achieved as a result of the resolved issues related to expensive onsite labour, paying overtime wages, as well as onsite resources and overhead (Lu, 2007; Mao et al., 2016; Pan & Sidwell, 2011c). When labourers work offsite, production productivity goes up because of a reduction in the expense of wasted time. McGraw-Hill-Construction (2011) stated that 17 % of construction contractors experienced cost savings of 11 % to 20 % due to the application of modular construction.

Safety: The reduction in onsite work activities associated with the use of modular construction can lead to a lower degree of potential risk and a decrease in the number of accidents, thus improving the working environment for labourers (Blismas et al., 2005; CII, 2011a). While the application of modular and offsite methods in construction projects will not completely eliminate accidents and risk, the risks become more predictable and could be more effectively managed in the fabrication, transportation, and onsite erection phases of a project than they can when traditional construction methods are employed (Arif et al., 2009). Many factors associated with modularization methods contribute to enhanced safety, such as less need for workers to operate on scaffolding or ladders, or to perform close work in tight spaces (Rogan et al., 2000).

2.5.2 Challenges of Modular Construction

Despite advantages of modular construction, there are limitations to this approach in construction projects is still limited (McGraw-Hill-Construction, 2011; Pan et al., 2008). A review of the literature revealed a number of inhibiting factors and challenges that must be addressed, including the following:

High Initial Cost: Cost has been identified as both advantageous and detrimental with respect to the use of modular construction. The advantages are explained in the previous subsection. Modularization concept is mentioned in many research studies as requiring a high initial expenditure (Goodier & Gibb, 2005b, 2007; Polat et al., 2006) or a significant capital investment (Pan et al., 2007). The major expenses are incurred from such processes as fabrication of modular components, transportation, and design consultancy (laili et al., 2013; Mao et al., 2016; Zhang et al., 2012). The perceived high cost of modular construction might disincline industry practitioners to apply modularization in future projects (Blismas et al., 2006; Pan & Goodier, 2011b). McGraw-Hill-Construction (2011) highlighted the fact that 8 % of design-build firms have experienced an increase of 22 % in total installed costs due to the implementation of modular and offsite technologies.

Regulations and Standards: The fact that regulations for modular construction fail to cover all aspects of fabrication methods, transportation techniques, and erection approaches discourages industry practitioners from adopting and applying modular methods (Ross et al., 2006). The application of modular construction can be increased through the creation of design standards and codes that can be applied and repeated for future projects (Jaillon & Poon, 2010; Johnsson & Meiling, 2009; Lawson, 2007; Lawson et al., 2014; O'Connor et al., 2015b). Cooperation among industry institutions and industry practitioners is necessary for the development of new standards, rules, design codes, and production guidelines that will encourage industry practitioners to consider implementing modularization concept when they are making decisions about future projects (Cao et al., 2015).

Design Freezing: The implementation of modular and offsite fabrication concepts in construction projects could be accompanied by technical difficulties, one of which is related to early design freeze (Blismas et al., 2005; Choi et al., 2016; O'Connor et al., 2015a, 2015b). All design documents should be completed before a fabrication process is begun because, from a tolerance management viewpoint, any late changes to the design are difficult to incorporate and accommodate, and may lead to interfacing problems, cost overruns, and schedule delays (Milberg, 2006).

Transportation: Transportation logistics has an important role in feasibility of modular construction systems. Before starting the design phase, the project team members should determine the module envelope, investigate the limitation of modules transportation from fabrication shop to final assembly site (Jameson, 2007; O'Connor et al., 2015a). In addition to studying general transportation requirements, maximum limit of distance for transportation, transportation method, and module dimensions' constraints should be investigated to avoid problems and damages to modules and their components (Boyd et al., 2013; Naqvi et al., 2014a; Naqvi et al., 2014b; Zhang et al., 2012). Also, cranes with a substantial carrying capacity or other hauling tools may be needed for positioning heavy modules. Other special accommodation for dealing with modules, such as jacking, may be required for lifting and handling. All these additional efforts might increase the total installed cost of employing modularization concept in construction projects (CII, 2011b).

2.6 Risk Factors Associated with Modular Construction

The literature provides references for analyzing risks associated with MC. Although certain risks are common to all types of construction projects, other risks are associated with specific types of projects because they require different management skills, technologies, and resources. Previous research studies have mentioned that specific type of construction contracts, such as a public-private partnership (PPP), can lead to some obstacles that are limiting real application of modularization concept. PPP projects are subject to country-related risks, such as government corruption, government intervention, public credit, political opposition, and foreign exchange fluctuation (Chan et al., 2010; Luo et al., 2015). Additionally, fragmentary nature of other contractual agreements such as Design-Bid-Build (DBB) can lead to significant amount of rework, schedule delay, and quality issues, due to lack collaboration, integration, and communication between main project parties at early design phase (CII, 2011a).

Lack of expertise is another risky factor that impedes modularizing construction projects. Arditi et al. (2000) indicated that lack of experienced contractors that are capable of building modular components and assemblies within design specifications and tolerance standards may lead to deficiencies in fabrication and assembly processes, improper assessment of modularization process capabilities, and unsuitable onsite handling and erection practices. Lack of expertise may result in severe conflicts between fabricators and designers at the initial project phases, failures in the fabrication stage, and delays in delivering modular components to site (Polat, 2008). These risks prevent the project parties from gaining the potential cost savings that may be obtained through application of modularization concept as a construction method.

Risks may also exist in supply chains involved in the construction processes of modular and offsite projects. A high level of integration and coordination among main project parties is necessary in order to maintain the required/contracted level of quality in terms of design documents, out-sourced materials, and delivered modular components and systems (Cus-Babic et al., 2014; Luo et al., 2015; Nadim et al., 2011).

Based on a survey research study, Li et al. (2013) has identified the distinct risks encountered in modular construction projects as follow: 1) in-plant risks: these are the factors involved in offsite prefabrication of modules and panels, including drawings supply time, drawings quality, material supply time, material quality, labour availability, labour skills, and fabrication equipment condition, 2) Onsite risks: these are the factors that have an impact on onsite assembly process such as temperature, wind speed, site condition, and construction equipment condition.

Other risks may affect the modularization performance include lack of skilled labour (Jaillon et al., 2008; Zhang et al., 2014), in-efficient lifting and hauling equipment (Arif et al., 2009; Jaillon et al., 2009; Pan et al., 2007), lack of governmental incentives (Arif et al., 2009; Zhang et al., 2014), and market demand and degree of acceptance among consumers of this type of construction (Li et al., 2013; Nadim et al., 2011).

2.6.1 Unique Risks to Modular Construction

Tolerance and alignment-related issues are unique risk events to modularized construction projects (Figure 2.4). The specified limits of dimensional and geometrical variabilities are known as tolerances (Ballast, 2007; BSI, 2011; Lawson et al., 2014). These limits are often used in order to target critical sources of variability and to control certain dimensional and geometric attributes of parts so that production goals can be met in way that balances cost, quality and customer satisfaction. The impact of not properly managing dimensional variability throughout modular lifecycle (e.g., fabrication, assembly, transportation and erection stages) can far outweigh the potential benefits of modular construction.

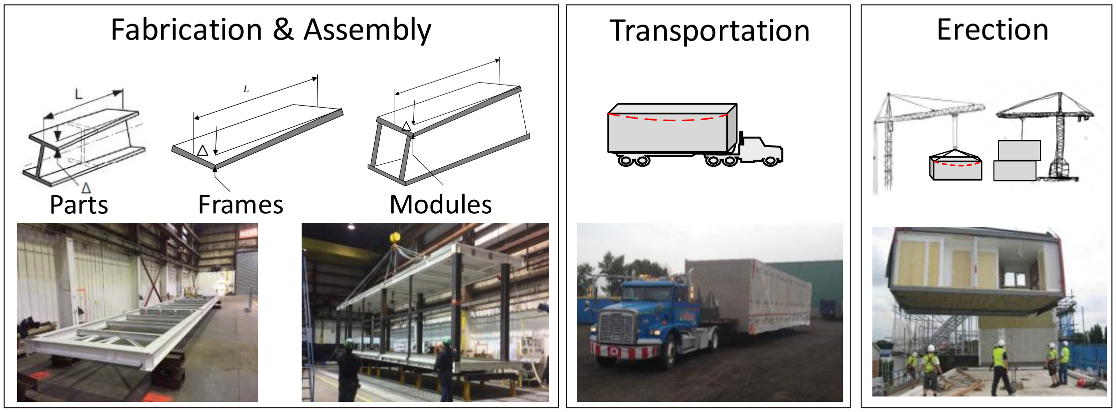


Figure 2.4. Excessive geometric variability in modular components and assemblies during different project phases.

The B2 tower at the Atlantic Yards in Brooklyn, New York, is an example that demonstrates the impact of tolerance-related risks and excessive geometric variability issues on the final assembled structure onsite. The construction company for the B2 project, Skanska, was responsible for designing and fabricating more than 900 modules in a multi-story apartment building, which then considered the world's tallest modular building (Skanska, 2014). The original design was based on the assumption that stiff and rigid modules would ensure no deformation during transportation and handling, which would improve the ease of erection. Unfortunately, once on site, the geometry of the modules was not conformant to the original design, which led to extensive rework to ensure proper fit up. The main notable challenges of dimensional and geometric variabilities are module-to-module misalignment (structural safety problem), façade misalignment (aesthetics issue), and damage to non-structural components (functionality problem). One of the main reasons of having such risks in the B2 project is the mismatch between the specified design solutions and actual process capabilities of manufacturer and contractor (i.e., designer employed design tolerances and solutions that neither fabricator nor erector could achieve). These issues resulted in cost overruns of $60 million and schedule delays of 20 months due to the significant amount of rework required to adjust, fix, and replace defective components (Skanska, 2014).

On the other hand, beside the impact of fabrication and onsite erection on excessive geometric variability, the transportation and handling phases, also, have an impact and contribution to this problem. Johnsson and Meiling (2009) examined the cause of defects encountered in prefabricated timber housing modules during transportation phase. In this study, there were notable effects of dimensional and geometric variability associated with transportation processes, where either doors or windows needed to be adjusted or walls were cracked due to the movement of the structure under the impact of dynamic loads. Even after providing adequate strength based on an assumed transportation load, some damage was still experienced, revealing the fact that transportation can create changes in the geometry of modules, leading to potential out-of-alignment, or even non-structural damage on modular components and assemblies. Clearly, rework and defects related to excessive geometric variability issues can be very problematic (Figure 2.5).

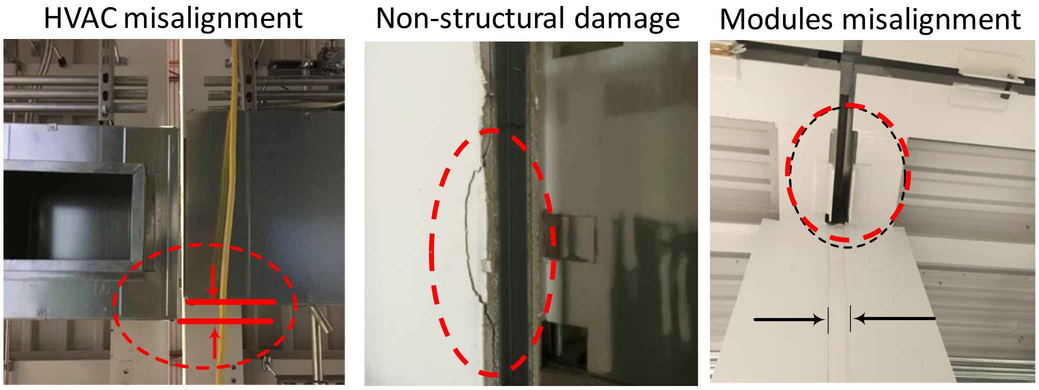


Figure 2.5. The consequences of excessive geometric variability.

Generally, tolerance-related risks and excessive geometric variability issues arise due to improper assessment of modularization process capabilities (e.g., the accuracy and precision of certain fabrication processes for achieving specified dimensions and assembly geometry), improper design tolerances (the selected allowable variation from nominal dimensions), inefficient design solutions (the module dimensions, lifting points, modularization percentage, etc.), and positional tolerance at site (e.g., ability of the crane to install the module in their accurate positions) (Lawson et al., 2012; Lawson et al., 2010).

2.7 Definition and Levels of Tolerance in Modular Construction

Tolerances are defined as the permitted amount of variation from nominal values or design specifications (BSI, 2011; Davidson & Shah, 2004; Henzold, 1995). There are two types of tolerance (Figure 2.6): 1) ***manufacturing tolerances***: which are required to produce a module within acceptable design specifications at fabrication phase, and 2) ***site*** **tolerances:** Which are required to achieve the overall safety and quality of assembled structure on site. The ***manufacturing*** tolerances are divided into two categories: 1) ***Dimensional Tolerance***: Allowable amount of deviation for a specific dimension (i.e., linear/distance, angular, or radial), 2) ***Geometrical Tolerance***: Permitted amount of deviation on a specific geometric property (i.e., straightness, flatness, perpendicularity, parallelism, etc.). The British Standard Institute (BSI) (BSI, 2011) divided geometrical tolerance into two categories as: 1) ***Essential Tolerances (ET)***: That are essential for mechanical resistance, strength, and stability of assembled module, and 2) ***Functional Tolerances (FT)***: which is required to fulfil other criteria such as fit-up and alignment onsite (FFT). The current research study has introduced a new category under FT, appearance-based FT (AFT), which is required to prevent damage of non-structural components (dry wall, concrete panel, MEP system, etc.) of a module during transportation, handling and erection (T/H/E). On the other hand, the ***Site based Tolerances*** are divided into types: 1) ***Positional Tolerance (PT)***: Maximum out-of-alignment in precisely positioning one module on another module due to limitations in the crane capabilities during erection phase at site, 2) ***Concrete Foundation tolerance (CT)***: Maximum permitted deviation of concrete foundation from specified level.

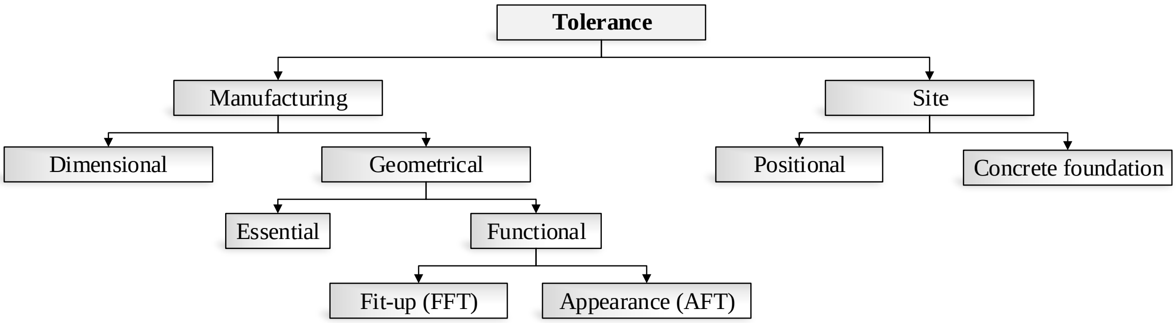


Figure 2.6. Type of tolerances in modular construction.

Essential tolerances (ET) are fixed/non-adjustable values, and they are dictated by standards due to safety requirements of the completed and assembled modules. Appearance-based functional tolerances (AFT), the new tolerance category, could have either fixed or flexible values. In commercial and residential sectors, the cases that follow the fixed values of AFT are: 1) 100% modularized units, and 2) completed and assembled structure onsite. On the other hand, the flexible values of AFT will be applied to modules with a modularization scope < 100% during T/H/E. The flexibility of AFT varies from one project to another, and from module to another in the same project depending on modularization scope and material properties. Fit-up based functional tolerances (FFT) could be either fixed or flexible values depending on the project approach and strategy to achieve final alignment at site. FFT could be flexible, if the modules are designed to be flexible by using, for example, adjustable connections. In this case, the modules geometry is expected to exceed the FFT limits, but without exposing the structure to any safety risks due to impact loads during T/H/E. Moreover, there will be site-fit costs associated with erection process to achieve final alignment at site. On the other hand, FFT could be dictated by tolerance standards (fixed values), at which all modules will be designed and built based on strict tolerance values.

This thesis considers the negative impact of both manufacturing and site based tolerance-related risks. In the next section, a brief explanation will be provided for the current approaches employed for managing excessive geometric variability issues in modular components and assemblies to be within acceptable tolerance ranges.

2.8 Current Approaches to Manage Tolerance-Related Risks

The management of tolerance-related risks and excessive geometric variability issues in modular construction projects is often approached either through specifying strict tolerances, based on standards and codes (Ballast, 2007; BSI, 2011), or applying ad-hoc strategies and trial-and-error solutions based on industry practitioner experience and insight (Silva, 2012; Smith, 2011). Current construction codes, such as ACI (2010), BSI (2011), and AISC (2016), apply strict tolerances for material, fabrication, and erection, in order to meet overall functional and assembly requirements. However, even with the application of tight and strict tolerances, the current codes and standards make it challenging to understand how tolerance-related risks accumulate and manifest themselves. This gap can be attributed to the fragmentary nature of construction projects, lack of process capability data, and lack of tolerance theory applied to construction (Milberg, 2006). Moreover, managing tolerance-related risks using the tight tolerances dictated by codes is a more tedious and time-consuming task for modular projects (Gibb, 1999), because the compatibility of geometric tolerances between modular components cannot be verified until final fit-up onsite occurs (Lawson et al., 2014). Furthermore, improving process capabilities to match the strict design tolerances can be prohibitively costly and too difficult to implement in practice (Milberg et al., 2002). Therefore, industry practitioners often use ad-hoc strategies and trial-and-error methods to achieve cost-effective solutions. Such solutions can involve either proactive strategies (e.g., anticipation of tolerance accumulation and dimensional variability) or reactive approaches (e.g., onsite adjustment) for managing out-of-tolerance and out-of-alignment issues. Although ad-hoc strategies can be effective, they require a priori knowledge, experience, and continuous improvement to be achieved successfully (Ballast, 2007; Silva, 2012; Smith, 2011). Table 2.1 summarizes some examples of proactive mitigation strategies (MSs) to manage and mitigate tolerance-related risks in MC projects.

Table 2.1. Summary of current employed mitigation strategies to manage tolerance-related risks.

Decision Maker	MS Type	MS Description
Owner	Project delivery	Integrated project delivery (IPD) Design-build (DB) Bid-design-build (BDB) Interface management (IM)
Designer	Design approaches	Module envelope Modularization scope Connection type Lifting method Lifting lugs Assembly method
	Prototyping	Prototyping (mock-ups)
Fabricator	Technology	3D imaging Total station
	Techniques	3D jigs Alignment testing Lifting method
Erector	Technology	3D imaging Total station
	Techniques	Installation sequence Temporary covering

2.9 Current Developed Decision Support Systems for Modular and Offsite Construction

Although the benefits of modular and offsite construction methods have been very well documented in the literature, there is a high reluctance rate from the industry practitioners and decision maker to adopt and apply those methods due to difficulty in ascertaining the real benefits such methods would add to a project (Goulding et al., 2013; Goulding et al., 2015; Li et al., 2013; Luo et al., 2015; Pan et al., 2011b). Most of decisions to use modularization as a construction method are based on experience, personal preference, familiarity, and anecdotal evidence rather than rigorous data (Idrus & Newman, 2002; Pasquire & Connolly, 2003).

Using modularization is relatively straightforward, for example, for the building of offshore platforms, for Arctic oil production, or for desert area facilities. However, in other cases in which the advantages are not so obvious, the owner's management personnel might not even consider modularization as an alternative to conventional methods. For this reason, decision support systems (DSSs) have been developed to help decision makers structure their decision-making process and improve the quality of information about modular construction projects (Turban et al., 2011). The optimal time for employing decision support tools is during the early project phases (e.g., front-end planning, feasibility and conceptual design phases) (Ammar et al., 2012). This timing allows project managers and industry practitioners to acquire an understanding of the decision problems and to make better choices based on a knowledge base related to a decision.

Numerous decision support systems (DSSs) and toolkits (Table 2.2) that have been developed to assist decision makers with their evaluation of the potential benefits and advantages of the use of modular and offsite technologies as a building method in construction projects (Gibb, 1999; Neale et al., 1993; Sparksman et al., 1999). Such DSSs and toolkits will support industry practitioners either in making: 1) strategic and high-level decisions about whether to apply stick-built or modular construction methods, or 2) tactical decisions to maximize project performance and benefits.The next section provides a summary of current developed DSSs and toolkits.

Table 2.2. Summary of current modularization DSSs and toolkits.

Reference	**Targeted sector**	**Developing stage**	**Application time**
	Strategic DSSs		
Tatum et al. (1987)	Industrial & building construction	Commercial	Early project
CII (1992)	Industrial	Commercial	Planning
Murtaza & Fisher (1994)	Industrial	Commercial	Planning
Gibb (1999)	Building construction	Research	Early project
Cigolini & Castellano (2002)	Industrial	Research	Early project
CII (2002)	Industrial	Commercial	Pre-project planning
Pasquire et al. (2005)	Building construction	Commercial	Early project
Pan et al. (2008)	Residential	Research	Early design
Chen et al. (2010)	Building construction	Research	Early design
Abdullah & Egbu (2011)	Building construction	Research	Early project
Elnaas et al. (2014)	Residential	Research	Early project
Choi & O’Connor (2015)	Industrial	Research	Early design
	Tactical DSSs		
Milberg (2006)	Civil infrastructure	Research	Early design

2.9.1 Strategic-Based DSSs

This section summarizes the current DSSs and toolkits developed to help modular construction practitioners and decision makers to better understand whether modularization is the right strategy for a project.

1. MODEX (Modularization Expert)

MODEX (CII, 1992) is a DOS-based DSS whose primary purpose is to assess potential benefits that modular construction may offer relative to the conventional stick-built method in industrial, petrochemical, and power generation industries. The decision support process focuses on three major questions: 1) whether the project can be modularized, 2) whether the project should be modularized, 3) what are the potential savings of modularizing the project. MODEX computes a confidence factor for a modularization decision based on different modular drivers. If the total weighted score is less than a set threshold value (e.g., ≤ 25 %), then the recommendation would be to use the conventional (non-modular) construction method. However, if the score is higher than the set value (e.g., > 25 %), then full or partial modularization can be used, and further decision analysis is needed, such as an economic study of cost savings or increases. MODEX is subject to a number of limitations: it is unable to handle quantitative and probabilistic input, and it has been validated for construction projects only in the petroleum and power generation industries but not yet for general construction projects. The accuracy of the MODEX results and output analysis is highly dependent on the accuracy of the answers to the questions at the input stage, which might prevent most construction managers from considering it reliable.

2. NeuroMODEX

An extension of the MODEX tool, NeuroMODEX (Murtaza et al., 1994) is a more refined DSS that was developed based on a neural network architecture for handling inexact and incomplete input data, i.e., abstract and poorly defined problems, during the design and development phase. The decisions that might result are (1) conventional with a high degree of confidence, (2) conventional with a low degree of confidence, (3) a low degree of confidence in partial modularization, (4) a high degree of confidence in partial modularization, or (5) extensive modularization. The results obtained from the neural network system have been compared with recommendations provided by experts. The validation tests demonstrated the accuracy of the neural network results. However, the tests were limited to 10 cases, and a need therefore exists to compile additional test cases in order to compare the performance of the system against the conclusions provided by the experts. The limitations of NeuroMODEX include its inability to provide an approximate cost estimate for a project if some degree of modularization is recommended or to predict the risk factors involved if some degree of modularization is adopted.

3. Modularization Model

The MODEX and NeuroMODEX tools were developed based on a qualitative method that lacks the quantitative capability of pinpointing the effect of modularization without the high cost of a traditional estimating approach during the early stages of a project. With the goal of filling the gap between the economic analysis of MODEX and the actual estimation process, Cigolini et al. (2002) proposed a new model for determining the cost variance between stick-built and modular construction. Their model was developed to support construction managers during the early stages of a project by generating quantitative results and a what-if analysis of stick-built and modular construction. The model involves four steps: 1) identifying the activities influenced by modularization, 2) identifying the modularization cost drivers, 3) evaluating the impact of modularization on those cost drivers, 4) comparing the cost of activities using a modular approach with the cost when traditional construction is employed. The proposed model has been validated using one Italian case study, and the results indicate potential benefits that can assist owners and contractors when they are performing an early quantitative (cost) analysis with the goal of choosing between modular and stick-built methods. A limitation of the proposed quantitative model is that its focus is on construction-related activities, such as module transport, site facilities, construction equipment, and work man-hours, while the engineering and fabrication phases, for example, the increase in design man-hours as a result of modularization, have not been included in consideration. As with MODEX, the accuracy of the output results is highly dependent on that of the input data.

4. PPMOF

CII has developed a computer-based tool called Prefabrication, Preassembly, Modularization, and Offsite Fabrication (PPMOF) (CII, 2002), which uses a Microsoft Excel spreadsheet, with the goal of helping a variety of construction industry professionals conduct a pre-project planning phase evaluation of the feasibility of modular and offsite approaches for industrial projects. The PPMOF decision-making process has three levels: Level I & II: strategic analysis, and Level III: tactical analysis. The purpose of the Level I strategic analysis is to provoke thought and provide insight into the potential for the use of PPMOF methods at the early planning phase of a project. Because Level II requires slightly more knowledge about the project, it is carried out later on during the pre-project planning and conceptual design phases. The Level III tactical analysis involves a cost comparison of different PPMOF strategies for a project: a determination of cost savings related to labour, schedule, safety, and quality and the calculation of additional costs associated with transportation, engineering, and coordination. The PPMOF evaluation processes include the following steps: (1) users weigh decision factors separately; (2) scores are combined for factor categories according to the relative importance weights; and (3) information is obtained about which factors could drive or impede the use of PPMOF for the project under consideration, rather than a decision or recommendation being given. Like feasibility analysis, decision-making with the use of PPMOF is essentially based on subjective evaluation by experienced personnel, which again means that the output results will be highly dependent on the input data.

5. IMMPREST

IMMPREST (Pasquire et al., 2005), which is an acronym for interactive model for measuring preassembly and standardization benefits in construction, is a computer-based toolkit that also uses a Microsoft Excel spreadsheet. This toolkit was developed for evaluating the benefits of standardization and preassembly (S&P). The toolkit comprises three distinct tools: an introduction and information tool (Tool A), an interactive benefit indicator tool (Tool B), and a benefit measurement tool using qualitative method (Tool C). Each tool introduces increasingly greater levels of detail and specificity with respect to the project and element being evaluated. The results are shown as bar charts for each benefit (higher) or disbenefit (lower) relative to a benchmark of 1.00, where 1.00 is the value given for the traditional option. The bar charts facilitate a comparison of the benefit associated with two specified options: traditional and S&P. The limitations of IMMPREST tool include its inability to predict the risk factors involved if some degree of modularization is adopted. Also, the decision making with the used of IMMPREST is based on subjective evaluation and personnel judgment, which again means that the output results will be highly dependent on the input data.

6. BSS

BSS (Pan et al., 2008), an acronym for build system selection, is a decision support tool that assists housebuilding organizations with the selection of appropriate build systems for their housing projects. This tool is recommended for use by key project team members within their organizational context and during the early design stages. The BSS tool provides more than 60 decision criteria clustered under the headings of cost, time, quality, health and safety, sustainability, process, procurement, and regulatory and statutory acceptance. The outcome of the BSS is an overall weighted score (non-cost comparison) of different building systems for different decision criteria. In general, the BSS tool reflects a structured, transparent, and robust decision-making tool for selecting a build system that will satisfy decision makers. However, the BSS tool has not been developed as user-friendly software, which makes it unsuitable for many companies.

7. IBS

IBS (Abdullah et al., 2011), an acronym for industrialized building selection, was developed based on analytical hierarchy process (AHP) theory. The IBS tool was created for use during the early design phase to help project managers and decision makers select the optimal type of industrialized building system based on a logical and quantitative approach. The outcome of the IBS is an overall weighted score (non-cost comparison) of different building systems for different decision criteria. The limitations of IBS include its inability to predict the risk factors involved in each building system. The decision-making with the use of IBS is essentially based on subjective evaluation by experienced personnel, which again means that the output results will be highly dependent on the input data.

8. CMSM

CMSM (Chen et al., 2010) is an acronym for construction method selection model, which was designed and developed to evaluate the feasibility of offsite construction method (strategic level) and explore an optimal strategy to determine to what extent building components should be manufactured offsite (tactical level) for a specific project. CMSM has the potential to assist decision makers in an appropriate construction method selection in construction projects, especially in the analysis of prefabrication and offsite adoption and optimization. CMSM has been applied in different case studies, and it demonstrates the effectiveness and practicability of the tool. However, the proposed model would be more powerful if it is further developed into a computer program or web-based program version, by which expected utilities for specified alternatives would be easily evaluated.

9. DSM

The decision support model (DSM) (Elnaas et al., 2014), a Microsoft Excel-based spreadsheet, was designed to assist key decision makers (e.g., contractors, owners, and designers) in making decisions about whether to use offsite manufacturing (OSM) or traditional onsite (TOS) methods as a construction strategy based on the evaluation of a number of key factors that have the most influence on project characteristics and specific requirements. The model is proposed for use during the early pre-project phase. The limitation of DSM tool is the narrow scope and limited application that it could be used only by housing building industry practitioners in UK, so it won’t be applicable for construction sectors in other countries.

10. Modularization Business Case Analysis

This tool was developed to enable an early-design-phase determination of the optimal proportion of work-hours to be moved offsite for industrial projects (Choi et al., 2015). The tool compares the benefits of using onsite versus modular construction methods with respect to technical feasibility analysis, schedule benefits analysis, relative man-hour costs at the site, and relative man-hour costs at the assembly yard. The output is the total installed cost (TIC) if stick-built methods are used, the TIC if modular methods are used, and the estimated total cost savings. The difference between this tool and tools previously developed is that, rather than being targeted at convincing the owners to use modular and offsite concepts in their projects, the new tool has been created from a modular and offsite perspective, with the specific goal of determining the optimal modularization percentage (amount of work completed offsite) to be performed at the fabrication facility, thus making it more modular oriented.

2.9.2 Tactical-Based DSSs

This section summarizes the tactical-based DSSs developed to support modularization decision makers and industry practitioners in identifying how best to implement MC on a given project.

1. Tolerance Management Tool

The tolerance management tool is the only DSS developed to support modular construction practitioners at tactical level by identifying the best approach to improve modularization performance and maximize its benefits in construction projects (Milberg, 2006). This tool (or five-step methodology) aims to resolve the mismatch between design tolerances and process capabilities by employing tolerance allocation and tolerance analysis techniques. The optimum time for applying this tool is at detailed design and engineering phase. The limitation of the tolerance management tool is the narrow scope of application by focusing on the strict and tight tolerance notion as the only scenario for building successful modular construction projects. The limitations of this toolkit include its focus on the strict and tight tolerance notion as the only scenario for building successful modular construction projects, and its inability to provide an approximate cost estimate for employing the proposed tolerance strategy or to predict the impact of tolerance failure modes on the overall project performance (cost, schedule, quality, etc.).

2.9.3 Summary and Knowledge Gap

Most of current knowledge about existing DSSs and toolkits is focused on the area of evaluating the feasibility (benefits and challenges) of using modular construction and offsite fabrication and then comparing the result of new methods with the results of traditional onsite method for strategic decisions purposes. However, the available strategic-based and high-level

DSSs and toolkits are limited in nature to only providing the industry practitioners with a “snapshot” of the expected results (benefits and disbenefits), and don’t provide the decision makers with a means of improving the impediments to modularization. On the other hand, although the tactical based DSSs and toolkits support industry practitioners by increasing their chances of success in implementing modularization if it is the right strategy, it focuses on the “strict and tight” tolerance notion to build modular systems and on design-based mitigating strategies (i.e., does not consider fabrication, transportation, and erection mitigation strategies and solutions). It also does not include a systematic process for evaluating the impact of tolerance-related risks in a quantitative manner on the overall project performance and a practical methodology for evaluating the effectiveness of the proposed mitigation strategies. Further improvement is therefore needed to: 1) address tolerance-related risks and excessive geometric variability issues’ impact on modularization performance, 2) identify optimum geometric variability (using a strict or relaxed tolerance approach) by optimizing the trade-off between offsite and onsite costs, and 3) evaluate mitigation strategy effectiveness in a systematic process designed to support decision-making at tactical level.

2.10 Quantitative Risk Assessment and Management Techniques in Construction Industry

This section provides an overview of risk assessment techniques and risk management methods employed in construction industry, and demonstrates how these techniques and methods can be applied to facilitate the proactive and efficient management of tolerance-related risks in modular construction projects.

2.10.1 Terms and Definitions Used for Risk Assessment

Risk can be defined from a number of perspectives, with its connotations being dependent on the context in which it is used. Aven (2011) defined risk as the possibility of deviation from an expected outcome or event. Outcomes that are unfavourable represent risk, whereas those that are favourable represent opportunity (Williams, 1996). Uncertainty is a term often used synonymously with risk and in relation to the management of risk. If the outcome was predictable, there would be no risk. Risk usually involves variability with respect to both the frequency and severity of the occurrence of the outcome (Raftery, 2003). CII (2010) introduced a popular method of cataloguing uncertainties, and therefore risks and opportunities, as known, known-unknown, and unknown-unknown situations or conditions. A known case represents risks that have a relatively high frequency of occurrence but relatively low severity (e.g., low labour productivity). A known-unknown case is an acknowledged situation that could affect an activity, but its potential for occurrence is not immediate nor would one normally expect it in the course of the activity. Known-unknown cases are best identified through a review of historical reports about comparable past projects. Extreme weather conditions, such as tornados, hurricanes, and floods, and highly adverse labour activities are examples of known-unknowns that have affected other projects. Unknown-unknown situations cannot be identified in advance (low probability of occurrence), and their potential impact can only be measured (catastrophic effects).

For this research, the risk will be defined as the probability that unfavorable outcome will occur, whereas the opportunity (positive impact) is excluded. The probability of occurrence of the risks will be always less than 100 %. On the other hand, uncertainty will be defined as the outcomes (work activities in CPM) that have 100 % probability of occurrence with uncertain impact.

2.10.2 Quantitative Risk Assessment and Management Techniques

In quantitative risk assessment (QRA), risks are evaluated using either deterministic or probabilistic methods (CII, 2012; Haimes, 2015; ISO, 2009; PMI, 2013; Taroun, 2014). In deterministic risk assessment method, probability of occurrence and impact of the identified risks are quantitatively estimated as percentages and added time/cost respectively (Hulett, 2010). The risk exposure is then evaluated using probability-impact (P-I) risk model. The results of deterministic risk assessment, which is based on single-point estimate of potential risk impact, will highlight the risks with high-impact for mitigation purposes. Probabilistic risk assessment using Monte Carlo simulation entails definition of the probability distribution function (PDF) of a potential impact (Vose, 2008; Yoe, 2011). A commonly used approach to systematically assess the quality of a fitted distribution on the collected data is goodness-of-fit tests such as Chi-Square test, Kolmogorov-Smirnov (K-S) test, or Anderson-Darling (A-D) test (AbouRizk et al., 1994; Banks, 1998; Law, 2014; Maio et al., 2000). Probabilistic modelling software (e.g., @Risk, Crystal Ball, and Primavera Risk Management) can be used to run Monte Carlo analysis. The results of the probabilistic approach provide additional information (e.g., confidence level, scenario analysis, sensitivity analysis, etc.) to support risk response planning and decision making.

Based on the risk assessment results, mitigation strategies are proposed to reduce risk impact on overall project objectives, through decreasing the probability of occurrence and/or impact. Different decision criteria (e.g., feasibility, performance, risk tolerability, risk attitude, etc.), which are defined by risk standards or companies' risk policy, can be employed to select the most effective solution.

2.10.3 Local and Global Risk Assessment and Management Techniques

In the quantitative risk assessment, risks are evaluated locally as the product of probability of occurrence and impact (ISO, 2009; PMI, 2013; Vose, 2008). Although the probability-impact (P-I) risk model is an effective approach in project risk assessment, it evaluates risks independently and individually (i.e., relationships among risks are not taken into account). Cervone (2006) modified the P-I model by adding a new dimension entitled "*discrimination*" to account for the impact of interactions among risks (i.e., global assessment). Although the modified P-I model is designed to evaluate the risk impact on the overall risk structure network of the project, it does not suggest a systematic process to objectively define and quantitatively evaluate the discrimination values, rather than using linguistic terms to represent interdependencies between risks. Other methods have been developed to define, represent, and evaluate the relationships (cause-effect relationship) among risks such as fault tree analysis (Diekmann et al., 1996; Volkanovski et al., 2009), failure mode effect analysis (Abdelgawad & Fayek, 2010), Bayesian belief networks (Kalantarnia et al., 2010; Meel & Seider, 2006; Trucco et al., 2008), and system dynamics (Rodrigues & Bowers, 1996). Although these methods clearly show the cause-effect relationship between risks, they still focus on either quantifying the risks independently and individually, evaluating the relationships in a qualitative manner, or disregarding the loop and chain reaction phenomena. Chen & Lin (2003) developed a model that uses the concepts of a design structure matrix (DSM) proposed by Steward (1981a, 1981b) and the analytical hierarchy process (AHP) proposed by Saaty (2003) to effectively identify and quantify the relationships among design tasks at the global level. The effectiveness of the proposed model has been demonstrated in different fields such as product design planning (Hung et al., 2008; Yang et al., 2014), supply chain improvement (Chen & Huang, 2007), team organization in concurrent engineering (Shi-Jie, 2005), project planning and scheduling (Yan et al., 2010), and project risk management (Fang & Marle, 2012a; Marle et al., 2013b).

The classical project risk management approaches aim to mitigate the local risk characteristics (probability of occurrence and/or impact) by proposing different mitigation scenarios (Apostolakis, 2004; Hulett, 2010; Muriana & Vizzini, 2017), which are then evaluated based on different decision criteria (e.g., feasibility, effectiveness, risk attitude, etc.) to select the optimal solution. However, the results of evaluating the interactions among risks at the global level can also provide a new perception of risk impact and prioritization, so that more complementary mitigation actions can be applied to manage the propagation behavior if any of the risks materialize (Fang et al., 2012a; Marle & Vidal, 2013a).

2.10.4 Dynamic Risk Assessment and Management Techniques

The quantitative risk assessment and management techniques are typically applied at early phases of construction projects (e.g., front-end planning, engineering and design) (Akhavian & Behzadan, 2014; Arashpour et al., 2016; CII, 2013a; Kang et al., 2013; Shahtaheri et al., 2017). However, the current risk standards and guidelines, e.g., ISO (2009), CSA (2007), and PMI (2013), recommend reviewing and monitoring the implementation of risk management plans during construction and operation & maintenance phases to determine: 1) the effectiveness of employed mitigation strategies, and 2) the need to update risk information when the context changes. Yet, such risk standards and guidelines usually do not provide detailed steps and practical methodologies of how to perform risk monitoring and revision in real-world projects. Therefore, it is the industries' responsibility to develop their own risk assessment frameworks and management methodologies, based on the project characteristics, purpose, scope, and environment, to monitor and review the risks' profile and revise the risk management plans.

The concept of dynamic risk assessment (DRA) is introduced to resolve the static nature of current classical risk assessment techniques which preclude any possible update of risks' input based on real-time information during construction, operation and maintenance phases of the project. DRA aims to integrate more realistic and accurate data of the main risk characteristics into the risk assessment and management processes, all of which provide more reliable risks' profile and efficient risk management plans. This assessment technique applies the concept of Bayesian theory to describe the uncertainty about risk parameters using Bayes' Theorem. The dynamic assessment and continual management are very well-known techniques and common practices in nuclear, chemical, and oil & gas projects, as these industry sectors deal with hazardous material, which a small risk event can escalate and result in catastrophic and abnormal accidents (Abimbola et al., 2014; Kalantarnia et al., 2010; Meel et al., 2006; Paltrinieri & Khan, 2016; Vinnem et al., 2012). Due to continued occurrence of major losses (e.g., human fatality, asset loss, environmental loss, reputation loss) in such projects, for example, Texas City refinery accident in 2005 (CSB, 2006) and Gulf of Mexico's Deepwater Horizon oil spill in 2010 (CSB, 2014), governments and regulatory standards are applying strict rules for assuring continual monitoring, review, and improvement of process safety management plans (CSA, 2007; IRGC, 2009; ISO, 2009). Even with the obvious differences between construction industry and other sectors (nuclear, petrochemical, oil & gas, etc.) (Table 2.3), employing dynamic risk assessment and management techniques in modular construction can help project risk managers and decision makers to efficiently reduce uncertainty of tolerance-related risks and proactively manage their impact, which will improve the modularization performance and maximize its benefits.

Table 2.3. A difference of perception of DRA in modular construction and other sectors.

	Oil & gas, nuclear, and chemical	Modular construction
Application time	Operation & maintenance.	Fabrication, transportation, and erection.
Risk severity	Abnormal, atypical, and extraordinary.	High.
Risk frequency	Highly improbable.	Probable.
Risk characteristics	Leakage, fire, dust, heat, and pressure.	Dimensional and geometric changes .
Risk indicators	Near misses, accident sequence precursors, and incidents.	Excessive geometric variability.
Consequences	Human fatality, asset loss, and environmental loss.	Out-of-alignment and non-structural damages.

2.10.5 Current Developed Risk Management Frameworks and Toolkits in Modular Construction

Although the literature review revealed that there is a variety of DSSs, models, and toolkits developed to evaluate the feasibility of modularization for construction projects and support industry practitioners to make strategic and tactical decisions, the application of modularization concept is still limited and below expectations (CII, 2014; O'Connor et al., 2014). Different risk assessment frameworks and risk management toolkits have been introduced for the systematic evaluation and management of modularization risks and challenges during early project phases. Li et al. (2013) introduced a framework for evaluating risks associated with modular construction in a quantitative manner using Fuzzy AHP (analytical hierarchy process) technique. The application of this framework will assist the house building industry practitioners and stakeholders in evaluating the offsite and onsite risks associated with modular construction and taking the proper action to mitigate their impact on the overall project cost and schedule. On the other, CII (2013a, 2013b) also developed an integrated project risk assessment (IPRA) toolkit for probabilistic risk evaluation and management using Monte Carlo simulation in construction projects. This toolkit is uniquely suited to enable an integrated project team to identify, assess, and subsequently mitigate significant risks in construction projects.

2.10.6 Summary and Knowledge Gap

Many research projects have been conducted with the goal of developing risk assessment and management frameworks/toolkits in order to support industry practitioners so that they can make better modularization decisions. However, these frameworks/toolkits are not without their limitations. For example, the risk management framework designed by Li et al. (2013) lacks an in-depth risk management process for supporting decision making and also is focused on independent and individual evaluation of risks (i.e., the relationships among risks are not considered in the risk assessment process). Moreover, the presented risk assessment process of this framework is designed to be performed on a static basis during early project phases. The risk management toolkit (IPRA) created by CII (2013a, 2013b) still lacks a practical process for identifying and evaluating the relationships among risks and does not include a methodology for updating the input information of main risk characteristics when more realistic data are available. Also absent is a systematic approach for optimizing risk response plans and decisions. Therefore, further improvement is needed to develop an efficient approach for thoroughly evaluating and managing tolerance-related risks at both local and global levels and a dynamic methodology for continually evaluating tolerance-based risk management plans and revising risk response decisions using Bayesian theory.

Chapter 3

Optimum Selection of Tolerance-Based Mitigation Strategy Using Strict and Relaxed Tolerance Approaches

3.1 Introduction

This chapter presents a systematic risk management framework for the proactive management of unique modularization risks. The developed framework includes identification and evaluation of tolerance-related issues and unique modularization risks in a quantitative manner, identification of the optimum geometric variability by addressing the trade-off between offsite and onsite costs, evaluation of mitigation strategy effectiveness based on tolerance theory, and representation of the results in 2D and 3D graphs to support the decision-making with respect to the optimum selection of mitigation strategy. A case study is used to demonstrate the proposed framework, and the results show that it can be used to effectively support industry practitioners to improve modularization performance and maximize its benefits.

3.2 Proposed Framework

This section summarizes the proposed risk management framework (RMF) (Figure 3.1), which is composed of three phases: (1) risk identification, analysis, and assessment, (2) scenario analysis, and (3) decision making. The application of the proposed RMF facilitates evaluating the impact of tolerance-related risks and excessive geometric variability issues on the key performance indicators of modular construction projects (e.g., cost, schedule, and quality), assessing MSs effectiveness, and representing the results in 2D and 3D graphs in order to support decision making process with respect to the optimal selection of mitigation actions. Although the RMF follows the standard and classical risk assessment and management techniques (CSA, 2007; ISO, 2009), these techniques are augmented by incorporating the tolerance identification and tolerance selection techniques in the risk assessment and management processes (see highlighted blocks in Figure 3.1). The next sub-sections explain the details of each step of the RMF.

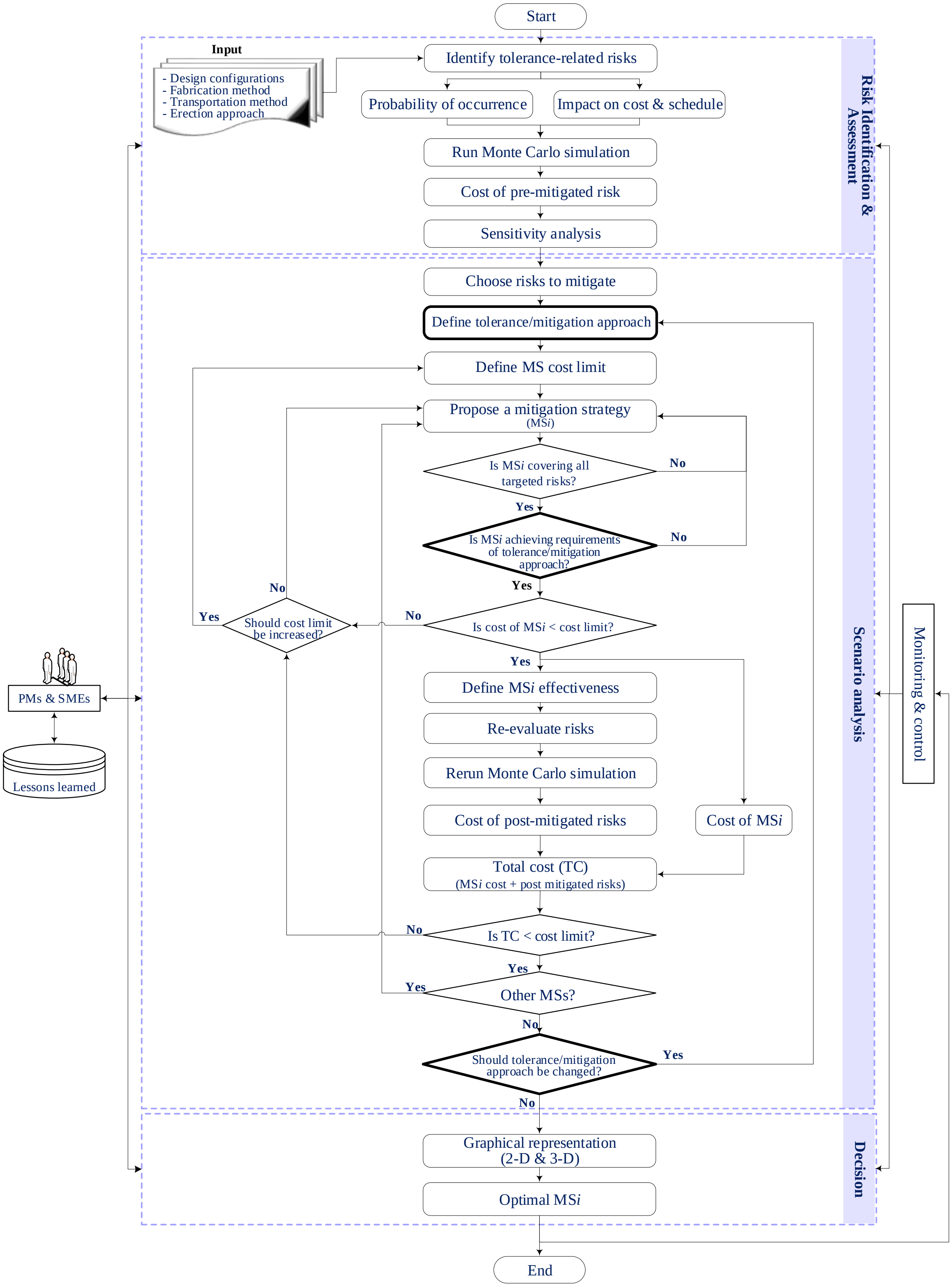


Figure 3.1. The proposed RMF for decision support of tolerance based MSs in MC.

3.2.1 Risk Identification, Analysis, and Assessment

Risk identification, which is the first step of classical project management (ISO, 2009; PMI, 2013), aims to identify potential tolerance-related risks that might have negative effects on dimensional and geometric specifications of modular components and assemblies. The risk identification process can be carried out using several techniques such as analogy (e.g., checklist, documentation review, brainstorming), heuristic (e.g., subject matter experts, open-ended questions, interviews), and analytic (e.g., failure mode effect analysis, cause-effect analysis, scenario analysis) (ISO, 2009; Muriana et al., 2017; Taroun, 2014; Yoe, 2011; Zou et al., 2009). In the risk analysis step, different approaches (e.g., qualitative, quantitative, or semi-quantitative) can be used to estimate the main characteristics of tolerance-related risks (probability of occurrence and impact). The main risk characteristics can be defined objectively using historical data or subjectively based on subject matter expert (SME) insight (Aven & Renn, 2009; CII, 2012, 2013b; ISO, 2009; Olechowski et al., 2016). In the risk assessment step, the risk value (product of probability of occurrence and impact) may be estimated using: 1) a deterministic approach (probability-impact risk model) through a single-point estimate of the potential impact, or 2) a probabilistic approach (e.g., Monte Carlo simulation) through a three-point estimate of the potential impact (Acebes et al., 2015; CII, 2012, 2013b). Monte Carlo simulation (MCS) allows project risk managers to quantitatively evaluate the impact of risk and uncertainty on the overall project objectives by creating a virtual population of projects that are just like the one under analysis through executing large number of simulation runs (Ang & Tang, 2007). MCS involves definition of the probability distribution function (PDF) of a potential impact on both cost and schedule (Vose, 2008; Yoe, 2011). A commonly used approach to systematically assess the quality of a fitted distribution on the collected data is goodness-of-fit tests such as Chi-Square test, Kolmogorov-Smirnov (K-S) test, or Anderson-Darling (A-D) test (AbouRizk et al., 1994; Banks, 1998; Law, 2014; Maio et al., 2000). The results of MCS will provide risk managers with additional data (e.g., likelihoods/percentiles of achieving project outcomes) to support the decision-making process.

3.2.2 Scenario Analysis

Based on the results of the previous step, risks with high impact will be targeted for mitigation. In the scenario analysis phase, tolerance/mitigation approach, MS cost limit, and potential MSs will be identified. The tolerance/mitigation approach (i.e., strict or relaxed) will be identified based on the project characteristics (e.g., efficiency and precision of quality control systems at fabrication plant and assembly yard, labour rates/skills/availability, schedule constraint, site attributes, etc.). Most of the current modular design practices apply "strict and tight" tolerances to achieve overall project objectives. In the strict tolerance approach, the modules will be designed and built to be within strict functional tolerance (FT) limits through all of the project phases. Using the strict approach (i.e., tolerance values dictated from standards) might: 1) reduce the amount of rework required to adjust the module geometry onsite, 2) increase the opportunity of building 100% modularized units (i.e., increase modularization scope/extent), and 3) speed up construction (alignment) time during the erection phase. However, the strict tolerance approach requires a high investment (time and money) in the planning phase to anticipate and solve tolerance issues, and in the fabrication phase to buy the assembly tools, jigs, and equipments needed to achieve the strict tolerances. The total expected cost of applying strict tolerance approach can be estimated as the summation of MS cost and cost of post-mitigated risks (see Equation 3-1).

$$\begin{aligned} &Total\ cost\ of\ strict\ tolerance\ approach \\ &\qquad = MS\ cost + cost\ of\ post\ mitigated\ risks \end{aligned} \tag{3-1}$$

On the other hand, a relaxed tolerance approach could be considered as an alternative to the strict approach. The relaxed tolerance approach focuses on designing and building modules that will accommodate geometric discrepancies by using, for example, adjustable or bolted connections. The module geometry is expected to exceed the strict functional tolerance (FT) limits, but without exposing the structure to high risk due to dynamic loads (i.e., transportation, handling, and erection loads). The relaxed tolerance approach might reduce fabrication cost (i.e., no need to use precise quality control systems such as 3D imaging or jigs) and reduce rework cost at job site compared to the strict approach (i.e., the modules will be designed to be easily/quickly fixed and adjusted). However, this approach may necessitate a reduction in modularization scope/extent to protect non-structural components (e.g., brittle materials such as windows, doors, drywall, etc. must be installed onsite). Therefore, there will be an expected amount of additional site work to: 1) bring the modules into alignment, 2) install shifted modularization scope. The total expected cost of relaxed tolerance approach can be estimated using Equation 3-2.

$$\begin{aligned} &Total\ cost\ of\ relaxed\ tolerance\ approach = MS\ cost + \\ &\quad cost\ of\ adjusting\ module\ geometry\ onsite + \\ &\qquad cost\ of\ instaling\ shifted\ modularizaion\ scope\ onsite + \\ &\qquad\quad cost\ of\ post\ mitigated\ risks \end{aligned} \tag{3-2}$$

Whatever tolerance approach has been applied, the final assembled structure onsite should achieve the following requirements: 1) structural integrity, 2) aesthetics and overall quality, and 3) performance and functionality. Therefore, the relaxed tolerance approach can be applied only for the fabrication, transportation, handling, and erection project phases (Figure 3.2).

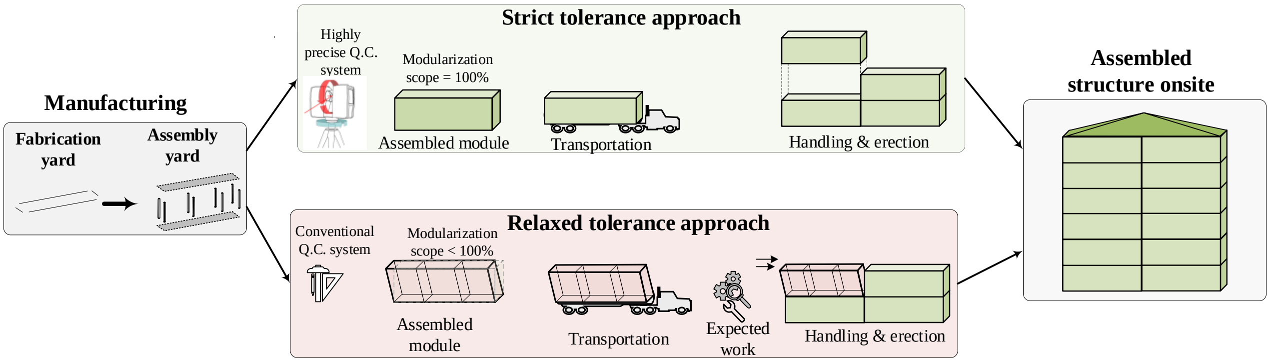


Figure 3.2. The scope of strict vs relaxed tolerance approach in modular construction.

After identifying the tolerance approach, the MS cost limit should be identified. The MS cost limit is mainly dependent on: 1) the pre-mitigated costs of the targeted risks, 2) the risk attitudes of the key stakeholders in the project, which can be represented in terms of contingency reserve, and 3) cost of performing risk analysis (Equation 3-3).

$$MS\ cost\ limit \leq cost\ of\ pre\ mitigated\ risks + contingency\ reserve + cost\ of\ performing\ risk\ analysis \tag{3-3}$$

Based on the identified tolerance approach and MS cost limit, a list of potential MSs will then be identified to reduce the probability of occurrence and/or impact of the targeted risks. The potential MSs should: (a) cover all targeted risks, (b) achieve requirements of the tolerance/mitigation approach, and (c) cost less than a cost limit. The effectiveness (manageability percentage) of candidate MSs can be evaluated based on either objective data (e.g., technical specifications of MSs) or subjective data (e.g., opinions of SMEs). Equation 3-4 shows how MS effectiveness can be estimated using objective data. The expected geometric discrepancy (EGD) represents the suitability of the proposed MS for achieving strict functional tolerances, and the current geometric discrepancy (CGD) represents the overall geometric deviation of the assembled module using current fabrication tools and assembly equipment in the fabrication shop.

$$Effectiveness\ of\ MS = \frac{CGD - EGD}{CGD} \times 100\% \tag{3-4}$$

After evaluating mitigation strategy effectiveness, Monte Carlo simulation will be repeated taking into account the impact of candidate MSs, and the post-mitigated risks will be evaluated. The feasibility of candidate MSs has to be rechecked by assuring that the total cost (which is the summation of MSs cost and cost of post-mitigated risks) is less than the cost limit (Equation 3-5).

$$MS\ cost + cost\ of\ post\ mitigated\ risks \leq Cost\ limit \tag{3-5}$$

3.2.3 Decision Making

Finally, the results of the scenario analysis can be represented in 2D and 3D graphs to support the decision-making with respect optimum selection of mitigation action.

3.3 Case Study: Modular Data Centre

The case study investigated in this paper consists of a one storey modular data centre comprised of 16 modules (8 identical Type-1 modules and 8 identical Type-2 modules) (Figure 3.3). Figure 3.4 shows the case study at different project phases. It should be noted the current case project represents a two identical modular data centre projects built in different locations in Ontario, Canada. At the end of fabrication and assembly phases of the first project, the owner's business and development team decided to increase the scope of the provided services from these modular data centres. So, the owner awarded the second project to same project parties. Based on the out-of-tolerance and out-of-alignment issues experienced in the first project, the authors developed the risk management framework to be employed in the second project, which is still in the early project phases, with the aim of reducing the excessive geometric variability impact on the overall cost and schedule. The purpose of the case study is to demonstrate the proposed RMF (Figure 3.1), recognizing that this RMF is generic and can be applied to a range of MC projects. Information concerning the case study was obtained from the industry partner. In addition, several site visits were conducted to shop during the fabrication and assembly processes, and to the job site during the module fit-up and alignment.

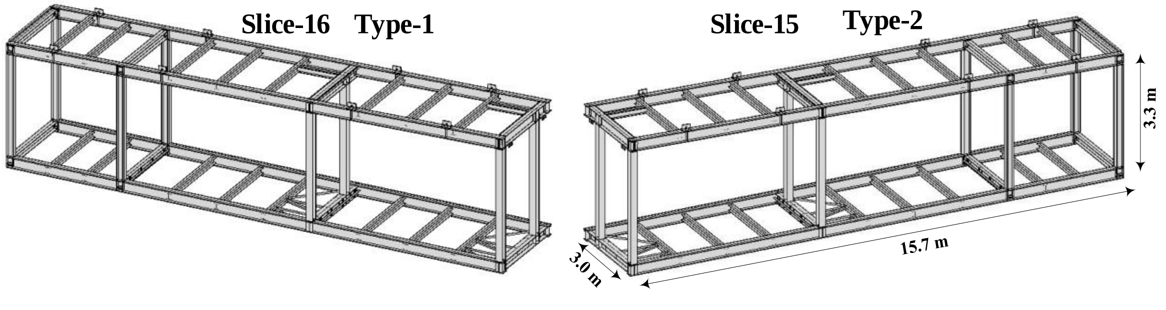


Figure 3.3. Structural configurations of modules used in the case study.

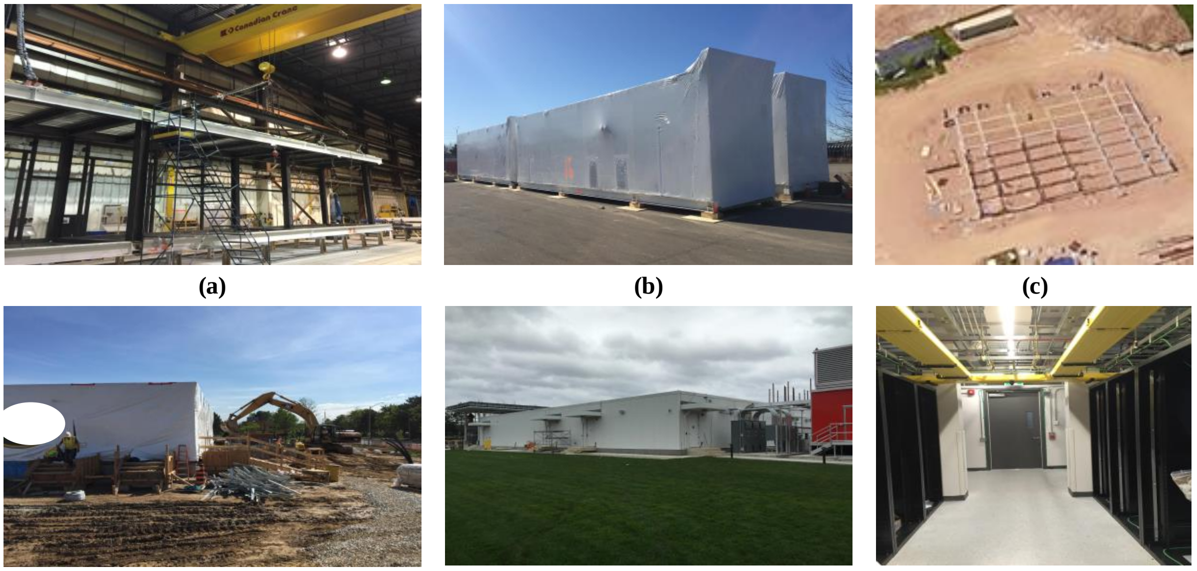

(a) **(b)** **(c)**
(d) **(e)** **(f)**

Figure 3.4. The case study at different project phases: (a) fabrication shop, (b) temporary storage area, (c) site preparation and building concrete foundations, (d) modules installation at site, (e) assembled building from outside, (f) finished building from inside.

3.3.1 Primary Challenges Associated with the Main Case Study Project

This section summarizes some of the tolerance-related problems and challenges that were encountered during the design, fabrication, and erection project phases of the main case study project. Data were gathered based on several meetings with industry partner of this research (fabrication team) and with the site-install company responsible for the onsite work.

Design phase

During the design phase, number of problems can arise as a result of change orders from the designer or the fabricator. The following are the main difficulties:

Risk of Change Orders from the Designer: Late design changes and modifications to the original design drawings can create alignment problems during the onsite installation phase. During fabrication phase, the design company changed the thickness of the drywall in order to meet fire resistance requirements. The original gap between modules was specified at 12.7 mm, but due to a change in the drywall thickness from 9 mm to 15 mm, the gap between modules became 0.7 mm (Figure 3.5). To accommodate this design modification, for placement on the foundations, the modules have to be moved further apart, which created a case of "growing building."

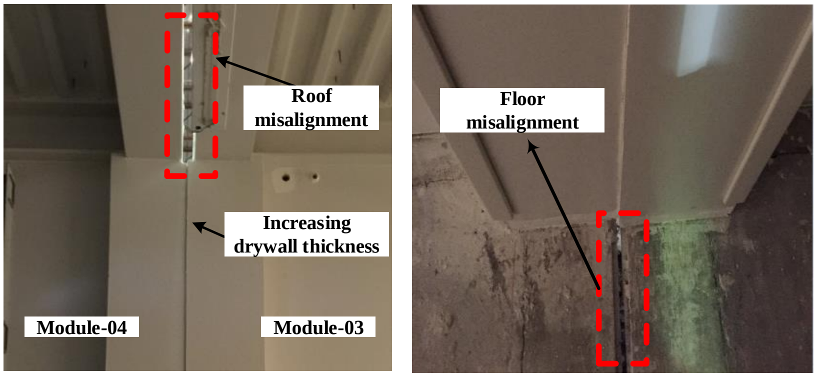


Figure 3.5. The impact of increased drywall thickness on the module-to-module alignment.

Risk of Change Orders from the Fabricator: The original dimensions of the modules as delineated by the designer were 3 m (width), 3 m (height), and 8 m (length). The fabricator offered to reduce the total fabrication cost if the modules length were increased to ≈16 m (Figure 3.3), which was then approved by the designer without ensuring that the new deign configurations/changes are conformant with fabrication and erection process capabilities. Maximizing the module size will reduce the number of modules, decrease the number of inter-module connections, and require fewer working hours for the onsite hook-up, all of which leads to an overall cost reduction. However, increasing the module size will increase transportation and logistic costs, distortional effect on module geometry due to impact loads, cranage cost, and the risk of rework.

Fabrication phase

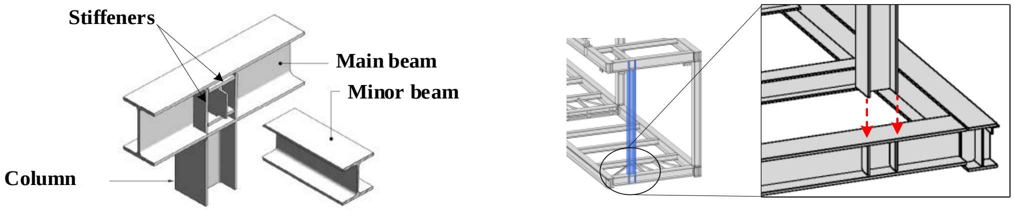
Excessive geometric variability issues can arise from a number of sources during the fabrication processes: lack of skilled labour, material properties, inadequate equipment, imprecise measurement tools, or deficiencies in the fabrication processes. The following are some of the problems encountered with the case study project during the fabrication phase:

Welding defects: Lack of proper quality control during fabrication was the emergence of, for example, inadequate welds (i.e., welds were not fully penetrated) which led to schedule delays and further inspection costs. Also, heat effect due to welding processes caused some tolerance related problems such as deformation and bowing on the modular components.

Lack of tolerance-based quality control strategy: The crew at the fabrication shop mentioned that alignment of roof frames was consistently off-centre from floor frames due to limitations in the fabrication processes and imprecision measurements (e.g., using measuring tape, level, and laser meter) to check the quality of the fabricated components. Also, there might be other reasons for this misalignment such as: 1) un-levelled controlling table (2D jig), 2) Fit-up of roof frame is not accurate enough due to lack of using precise tools to check the plumbness of the column and position of roof frames, 3) Crane-lifts might cause distortion to structure.

Supplier's risk: There was no a strict quality control strategy/tool to check the conformity of dimensional and geometric values of outsourced frames and sub-assemblies whether they are within acceptable tolerance range before starting assembly process. The fabrication company was checking the overall dimensions, spacing, and location of the outsourced sub-assemblies and frames using imprecise tools (e.g., laser meter and measuring tape).

Risk of using welded connections: the design company used moment-resisting joints (welded connection) with stiffener plates to increase their rigidity for seismic requirements (Figure 3.6.a). Generally, welded connections with stiffeners have three main concerns: 1) heat effect due to welding processes, 2) positional accuracy of stiffeners, and 3) quality of welds. The first two concerns can create FFT related problems, and the third one can lead to rework issues. Regarding heat effect, welded joints with stiffeners will add more heat on the module components during welding process, which may cause a certain amount of shrinkage and deformation. The shrinkage and deformation values in many circumstances are only a minor problem but angular distortion, bowing and twisting can present considerable alignment problem at erection phase. On the other hand, the positional accuracy of stiffeners may affect the positional accuracy of other modular components. For example, there are some critical parts such as columns and roof frames will be installed based on the stiffeners locations (i.e., stiffener location will be considered as a benchmark location or a point of reference to assemble modules within acceptable geometric variation ranges) (Figure 3.6.b). Therefore, any positional errors in the stiffeners might lead to positional errors in other module components.



(a)

(b)

Figure 3.6. Used connection in case study project: (a) connection between column & beam, (b) stiffeners' location as a reference point for column fit-up.

Inefficient use of controlling table: The entire skeleton-based modules were assembled on a controlling table (2D jig), while they are sitting on minor beams instead of the main beams that are designed to sustain the loads (Figure 3.7). Thus, the floor frames may experience distortional damages and geometric changes, which will lead to misalignment problems at site.

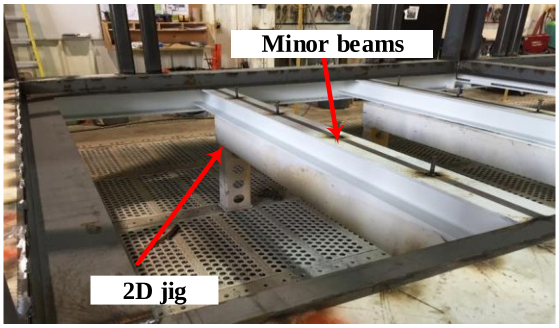


Figure 3.7. Minor beams of a module are sitting on 2D jig for assembly processes.

Erection phase

The following are some of the encountered challenges during module-to-module and module-to-site alignment processes at the project site:

Inclement Weather: Excessively poor weather conditions (rain, snow, wind, etc.) had the greatest impact on the module-installation process, causing a delay in the arrival of the module at the site, damage to non-structural components (e.g., MEP systems, servers equipment, and finishing materials), forcing the postponement of site-installation tasks, and creating unfavourable conditions for moving and adjusting the modules, thus increasing the risks associated with safety.

Lack of tolerance-based quality control strategy: The modules have been installed without performing any quality control check to assure that modules arriving on site are within acceptable geometric variation limit. When the modules arrived at the site, the bottom profile (floor frames) of some modules experienced some geometrical deviations, which led to the tedious process of custom shimming each module in order to ensure that they were horizontally level with the foundations (Figure 3.8). Thus, there was significant amount of rework and schedule delay to achieve complete alignment between modules and foundation.

Figure 3.8. Installation of steel shims to cover the gap between modules and foundation.

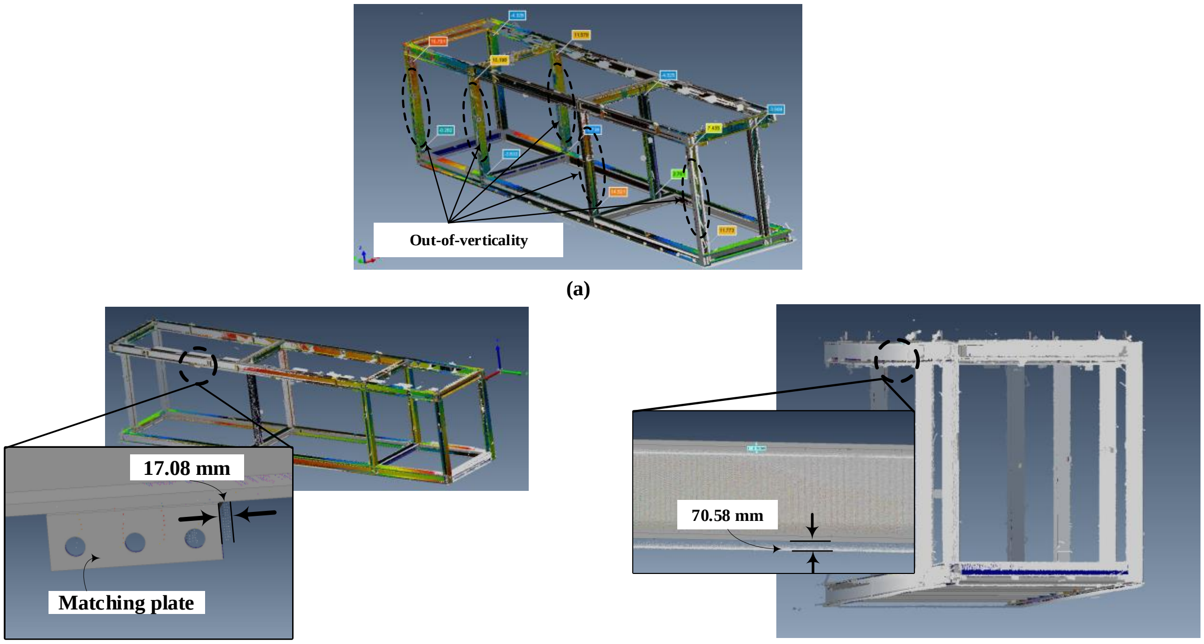
3.3.2 Risk Identification, Analysis, and Assessment

The main tolerance-related issues and unique modularization risks that might be encountered in MC projects are summarized in a risk register table (see Table 3.1). For the case study project, risks were identified and refined based on meetings with the industry partner (fabrication team), meetings with the site-installation and erection company responsible for onsite work, and literature review. It should be noted that the current research approaches the identified risks from a modular perspective only (i.e., risks due to either tolerance-related issues, or uniqueness of modularization processes). It is worth mentioning that this research did not consider any geometric and dimensional variability in modular components and assemblies due to temperature differences. These variabilities could, however, be considered within the current framework either as a separate risk or possibly within Risks R4 or R5 if temperature issues were thought to be relevant for a particular project.

Table 3.1. List of tolerance-related problems and unique modularization risks in modular construction projects.

Risk ID	**Risk name**	**Category of Impact**	
		Schedule	**Cost**
R1	Unclear design documents	Delay	Extra cost
R2	Errors in design documents	Delay	Extra cost
R3	Late design changes	Delay	Extra cost
R4	Sub-Assemblies (parts) have excessive geometric variation	Delay	Extra cost
R5	Non-volumetric units (frames) have excessive geometric variation	Delay	Extra cost
R6	Volumetric unit (module) has excessive geometric variation	Delay	Extra cost
R7	Welding defects	Delay	Extra cost
R8	Weather-proofing shroud has defects	Delay	Extra cost
R9	Foundations have excessive geometric variation	Delay	Extra cost
R10	Bad weather condition at site	Delay	Extra cost
R11	Module has non-structural damage	Delay	Extra cost
R12	Module has a structural damage	Delay	Extra cost
R13	Module-to-module alignment time is increased	Delay	Extra cost
R14	Module-to-site alignment time is increased	Delay	Extra cost
R15	Mechanical, electrical, and plumbing (MEP) fit-up is increased	Delay	Extra cost
R16	Increased working hours due to rework increase accidents	Delay	Extra cost

The next step of risk identification is to analyze the probability of occurrence and impact of the identified risks. The assessment of main risk characteristics (probability of occurrence and impact) was performed based on: 1) available data for the current case study project (e.g., CPM schedule, quality control reports, fabrication and erection cost codes, and change request extra reports), 2) previous lessons learned documents provided by the industry partner, 3) rational assumptions based on face-to-face meetings and observations during the fabrication and erection phases of current case study project, and 4) available information from the literature (CII, 2001, 2005; COAA, 2003; RSMeans, 2012). In addition, for some of the registered risks (e.g., R4, R5, and R6), laser scanning technology was used to estimate the main risk characteristics (probability of being out-of-tolerance and required amount of rework) through performing deviation analyses for modular components and assemblies. For example, as-built data for the main structure of one of the modules was collected using a FARO LS 840HE laser scanner during the assembly processes at the fabrication shop, and as-designed data was extracted from a building information model (BIM). The commercial software PolyWorks® was used to perform deviation analysis. It was found that the main structure of the module had the following out-of-tolerances: 1) five columns out of eight had deviations from vertical that exceeded the tolerance limit, 2) three matching plates out of seven had positional error, and 3) one roof frame beam had excessive deflection along the length of the module (Figure 3.9). Based on these measurements, it was estimated that the probability of out-of-tolerance was 62.5% for the columns, 42.8% for positional errors of matching plates, and 25% for excessive deformation of the main roof beam. Assuming these three out-of-tolerances have the same relative importance on the overall geometry of assembled modules, the geometric average can then be used to estimate the probability occurrence of Risk R8 as 40.59% (see Table 3.2).



(a)

(b)

(c)

Figure 3.9. Results of deviation analysis using PolyWorks®: (a) verticality of columns, (b) location of matching plates, and (3) deformation (bow) of roof frame.

The expected impact is evaluated as the required amount of rework to fix, adjust, or replace defective parts, frames, or modules. The rework cost (RC) includes direct cost (DC) and indirect cost (IC) (Equation 3-6). The direct cost (DC) can be expressed as the summation of cost impact (CI) and schedule impact (SI) (Equation 3-7). The cost impact (CI) can be expressed as the summation of labour cost (LC), material cost (MC), and equipment cost (EC) (Equation 3-8).

$$RC = DC + IC \tag{3-6}$$

$$DC = CI + SI \tag{3-7}$$

$$CI = LC + MC + EC \tag{3-8}$$

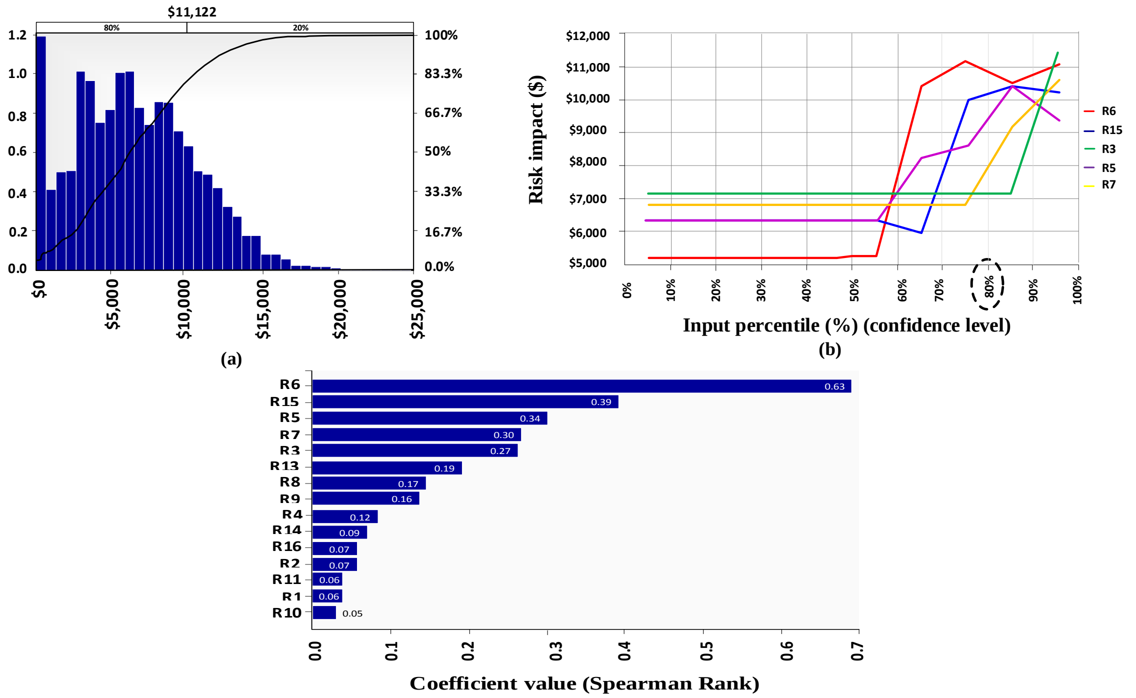
The calculated rework represents the expected (most likely) impact on schedule and cost. For instance, the rework cost of Risk R8 is estimated using the available information of the current case study project. Based on the actual CPM schedule of the RICC-Mississauga Project, the assembly time for the main structure of six modules was longer than the estimated time for the early project phases. The average added time (i.e., schedule impact) due to the occurrence of Risk R8 was thus estimated as 1.2 days (Table 3.2). On the other hand, the cost impact of Risk R8 is evaluated based on the cost codes for fabrication and assembly processes of the RICC-Mississauga Project. To fix the excessive geometric variability issue in the assembled modules due to the occurrence of Risk R8, three labourers with a rate of \$65 per hour are required for 1.2 days. The cost impact of Risk R8 was thus estimated as \$2,160 $[3\ labourers \times \$65\ per\ hour \times 1.2\ days (8\ hour\ per\ day)]$ (Table 3.2). Due to lack of shared and available information needed to generate optimistic and pessimistic values for impacts, rational assumptions were made to develop these values, for the purpose of demonstrating the RMF application. The pessimistic values of tolerance-related risks are assumed to be varying from 1.3 to 1.6 of the estimated most likely value, and the optimistic values range from 0.6 to 0.85 of the calculated most likely, depending on the occurrence of tolerance-related risks. Table 3.2 summarizes the values assigned to the probability of occurrence and the potential impact range with respect to cost and schedule for each risk. It should be noted that the impacts on cost and schedule were estimated on a per volumetric module basis. Generally, the main characteristics of tolerance-related risks (probability of occurrence, impact on cost, and impact on schedule) in the risk register table (Table 3.2) vary from one project to another based on different factors: 1) defined tolerance approach, 2) selected design solutions (modules envelope, modularization scope, type of connections, and type of material), and 3) employed quality control systems used in fabrication and assembly processes.

Table 3.2. Probability and impact ranges for registered risks.

Risk	Probability (%)	Impact					
		Schedule (days)			Cost ($)		
		Optimistic	Most likely	Pessimistic	Optimistic	Most likely	Pessimistic
R1	0.77[1]	0.85	1.10[2]	1.27	220	270[5]	330
R2	5.39[1]	0.50	0.65[2]	0.75	250	310[5]	380
R3	10.05[1]	0.50	0.65[2]	0.75	1,980	2,470[5]	2,970
R4	17.67[3]	0.35	0.35[2]	0.60	610	640[4&6]	1,030
R5	37.70[3]	0.80	0.85[2]	1.45	940	990[4&6]	1,590
R6	40.59[3]	1.10	1.20[2]	1.95	2,065	2,160 [4&6]	3,470
R7	18.75[1]	0.60	0.75 [1&2]	1.05	910	1,140 [4&6]	1,600
R8	16.60[1]	0.50	0.65[1&2]	0.95	490	620[4&6]	870
R9	31.25[1]	0.20	0.25[1]	0.35	440	550[1&4]	770
R10	4.54[1]	0.15	0.20[1&2]	0.25	150	190[1]	260
R11	5.35[1]	0.09	0.10[1]	0.15	290	360[1]	510
R12	0.01[1]	4.80	6.10[1]	8.40	4,500	5,000[1]	7,500
R13	37.50[1]	0.10	0.15[1]	0.20	1,040	1,340[1&2]	2,010
R14	12.50[1]	0.10	0.10[1]	0.20	550	720[1&2]	1,080
R15	31.25[1]	1.10	1.20[1]	1.80	810	1,020[1&2]	1,530
R16	0.13[1]	1.50	1.70[4]	2.85	3,430	3,810[5]	6,480

1. Rational assumption based on several observations and meetings with industry partner during fabrication and erection phases
2. Available data of current case study (e.g., CPM schedule, QC reports, fabrication and assembly cost codes, and change request extra reports) and lessons learned documents shared by industry partner
3. Deviation analyses using laser scanning technology
4. CII: Construction industry institute (CII, 2001, 2005)
5. COAA: Construction Owners Association of Alberta (COAA, 2003)
6. RS cost Data (RSMeans, 2012)

In order to perform a probabilistic risk assessment using Monte Carlo simulation, the *@RISK®* software was employed because of its affordability and compatibility with MS Project. A triangular distribution was used to represent the cost and schedule impact ranges due to lack of available data for distribution fitting (i.e., goodness-of-fit tests). The results of the Monte Carlo analysis after 10,000 iterations at an 80% confidence level (i.e., 80th percentile) revealed that the total expected cost of risks on a volumetric module is $11,122 (Figure 3.10.a). The current research adopted the 80th percentile as it covers a wider range of potential impacts on cost and schedule than 50th percentile typically used by industry (Figure 3.10.b) (Hulett, 2010; NASA, 2015). The selection of the percentile (or confidence level) on the extracted results of the Monte Carlo analysis can be identified based on different factors such as the accuracy rate of the risk input data; the risk appetite/attitude of the project managers (whether they are risk averse, natural, or seekers/lovers); and risk profile of the targeted risks (low, medium, or high-impact risks). In this research, the results of the probabilistic risk assessment are extracted at the 80th percentile to illustrate how significant the impact of these risks are on the overall project performance and on total installed cost; and to offset the impact of uncertainty in the estimation of the main risk characteristics (probability of occurrence, impact on cost, and impact on schedule). The risks can also be prioritized through a sensitivity analysis. Figure 3.10.c (tornado graph) shows that Risks R6, R15, and R5 have the greatest impact on driving the schedule and cost of a volumetric module.



(a)

(b)

(c)

Figure 3.10. Monte Carlo analysis results: (a) probability distribution function (PDF) of total cost of risk, (b) risk value at different percentiles, and (c) tornado graph correlation coefficients.

3.3.3 Scenario Analysis

Before implementing any MS, it is important to consider the MS cost compared to its effectiveness of reducing the risk impact. Assuming (for example) that Risk R6 will be targeted for mitigation purposes as it has the highest impact on total project cost, the next step is to identify the tolerance/mitigation approach (strict or relaxed). In the current case study, the modules were designed based on the relocatable building (RB) concept (i.e., this project can be disassembled, transported, and erected in different provinces in Canada). Therefore, strict tolerances were used on this project (i.e., the modules were designed to achieve precise final alignment with zero rework on site). Another reason for applying strict tolerances in the case study project is the fragmentary nature of contractual agreement of project delivery (design-bid-build). Even with the strict approach, misalignments, misfits, and large gaps between modules, matching plates, and columns were observed during erection phase at job site (Figure 3.11). These misalignments mainly resulted from poor definition of tolerance values in the design phase, imprecise fabrication and assembly methods/equipment, and inefficient management of overall geometry of the assembled structure at job site.

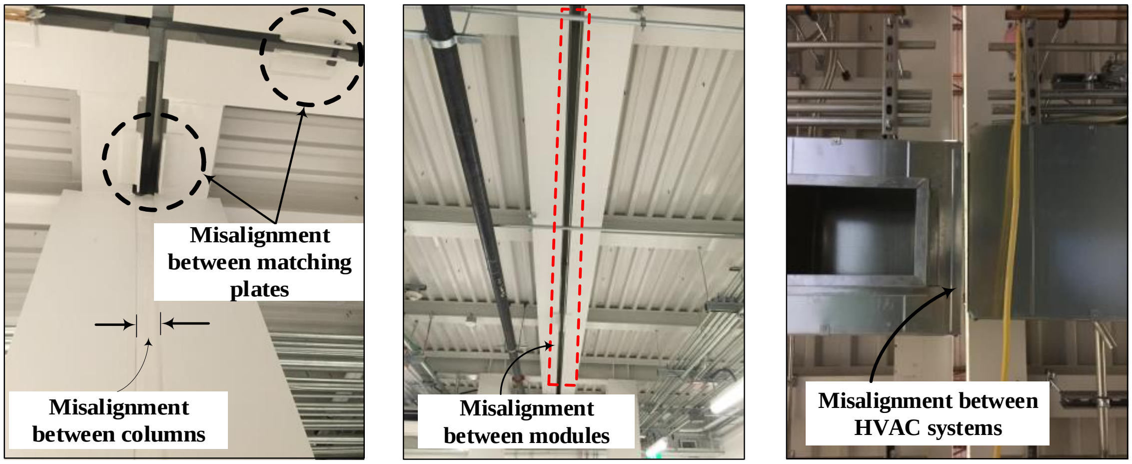


Figure 3.11. Misalignment issues at erection phase of current case study.

After identifying the tolerance approach, the MS cost limit should be identified. Based on Equation 3, the current research defined the MS cost limit as the value of pre-mitigated risks for the current case study ($11,122 × 16 modules = $177,952), which includes the contingency reserve (risk attitude) through extracting the total cost of risks at specific percentile (80% confidence level) (Figure 3.10.a). However, the cost of performing risk analyses in the current case study project (RICC Project) is not included in the MS cost limit estimates because it is assumed to be small value compared to other cost elements. However, in high-rise buildings (e.g., B2 Project) and large scale projects, the cost of performing risk analyses should be included in the definition of the MS cost limit as there will be a considerable amount of effort needed to identify, analyze, assess, and manage the modularization risks. After identifying the MS cost limit, a list of potential MSs, which should achieve tolerance approach and cost less than cost limit, is developed (see Table 3.3). The current research paper has introduced a new assembly method (parallel assembly) as a proactive mitigation strategy that will help the fabricator to build and assemble modules compliant with dimensional and geometrical design tolerances. In the current case study, the modules were built by assembling columns with floor frame, and then roof frames with columns (i.e., vertical/bottom-up assembly) (Figure 3.12.a). In vertical assembly, the fabricator has to check: 1) plumbness of columns, and 2) location of roof frame. This method of assembly can be changed to parallel assembly (frames-to-beams) to have more control on the overall module geometry during assembly (Figure 3.12.b). In the new assembly method, the columns are installed with the frames, thus eliminating the need for workers to check the plumbness of each column and the location of roof frame as vertical assembly. Also, the plumbness of side frames can be controlled "easily" using fixturing tools and clips rather than expensive assembly equipment (e.g., 3D jigs).

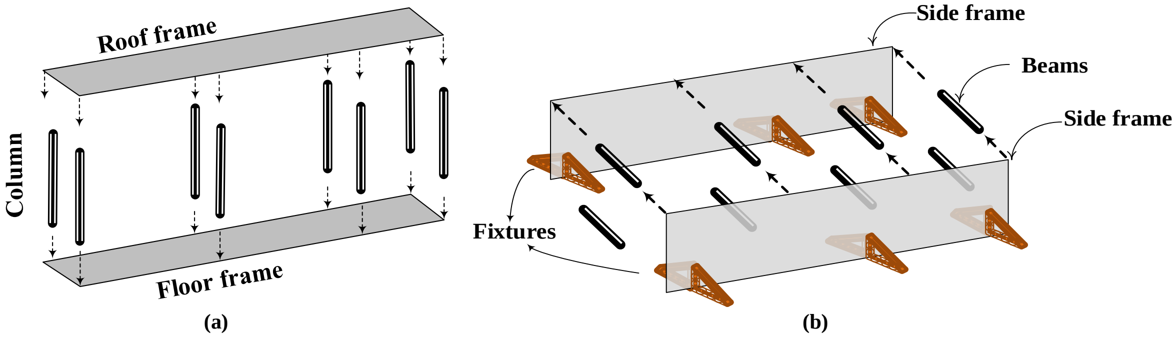


Figure 3.12. Module assembly method: (a) vertical assembly, (b) parallel assembly.

The effectiveness of candidate MSs is then evaluated based on either objective data (e.g., technical specifications of MSs) or subjective data (e.g., opinions of SMEs). For example, the effectiveness of 3D imaging technology is evaluated based on technical specifications of laser scanner to capture as-built data (±3 mm) and the accuracy of deviation analysis software to perform registration and comparison between as-built and BIM (±3 mm). Therefore, the overall accuracy of 3D imaging technology can be estimated as ±6 mm (i.e., the expected geometric discrepancy (EGD) of a module built using 3D imaging technology as a quality control tool is ±6 mm). On the other hand, the current geometric discrepancy (CGD), which is representing the overall geometric deviation of the assembled module using current fabrication tools and assembly equipment in the fabrication shop, is evaluated as 34.75 mm based deviation analysis results. It is worth mentioning that 3D imaging (laser scanning technology) can be considered as: 1) a tolerance identification tool by checking the compliance between tolerance standards and geometric variabilities in modular components and assemblies, and 2) a mitigation strategy by identifying the amount of displacement and/or rotation required to adjust the excessive geometric variability issues. Using Equation 3, the effectiveness of 3D imaging in managing Risk R6 is then evaluated as 82.73% (Table 3.3). Table 3.3 summarizes the effectiveness of different MSs and their impact on the tolerance-related risks. It should be noted that effectiveness of 3D imaging and 3D jigs was evaluated based on the available technical specifications, and rational assumptions were made to develop effectiveness of the remaining MSs.

Table 3.3. Summary of the impact of each MS on the tolerance-related risks.

Mitigation strategy	**Risk events**															
	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**
3D imaging				64.1%	74.7%	82.73%			76%				76%	76%		60%
3D Jig				70.1%	85.6%	79.5%							80%	80%		
Prototyping (Mock-ups)	45%	60%	85%			30%	50%				40%		40%	40%		
Precisely fabricated connection					60%	50%	45%						45%	45%		
Parallel assembly					30%	75%							30%	30%		

Once the effectiveness of each MS has been identified, the cost of tolerance-related risks is re-evaluated by re-running the Monte Carlo simulation (i.e., evaluating the cost of post-mitigated risks). Table 3.4 provides a summary of the assigned costs of each MS, cost of pre-mitigated risks, current geometric discrepancy (CGD), cost of post-mitigated risks, and expected geometric discrepancy (EGD).

Table 3.4. Summary of costs of different MSs, risk values, and expected geometric discrepancy.

MS	**MS cost**	**Pre-mitigated risks value**	**CGD**	**Post-mitigated risk value**	**EGD**
3D imaging	\$20,000 ^{1}	\$177,952	34.75 mm	\$82,490	± 6 mm ^{1}
3D Jig	\$37,500 ^{1}			\$91,140	± 5 mm ^{1}
Prototyping (Mock-ups)	\$154,270 ^{2}			\$125,480	± 20 mm ^{2}
Precisely fabricated connection	\$25,600 ^{2}			\$105,840	± 8 mm ^{1}
Parallel assembly	\$16,000 ^{2}			\$106,970	± 10 mm ^{2}

1. Based on technical specifications and available information of MS.
2. Based on rational assumptions.

After evaluating the cost of post-mitigated risks, the feasibility of each MS is re-examined to make sure that the sum of the MS cost and cost of post-mitigated risks are less than cost limit (Equation 3-5). Based on the results in Table 3.4, for example, the prototyping (mock-ups) MS will be excluded, on the basis that the cost limit is exceeded.

3.3.4 Risk Response Decision

In the final phase of the RMF implementation, the results can be represented in 2D and 3D graphs to support decision makers in choosing the optimal MS (see Figure 3.13 and Figure 3.14). Based on the identified MS cost limit and acceptable geometric discrepancy (functional tolerance requirements), the potentially viable MSs are 3D imaging technology and 3D jig (Figure 3.13). The optimum MS is the one that has the least initial cost, which is in this case is 3D imaging.

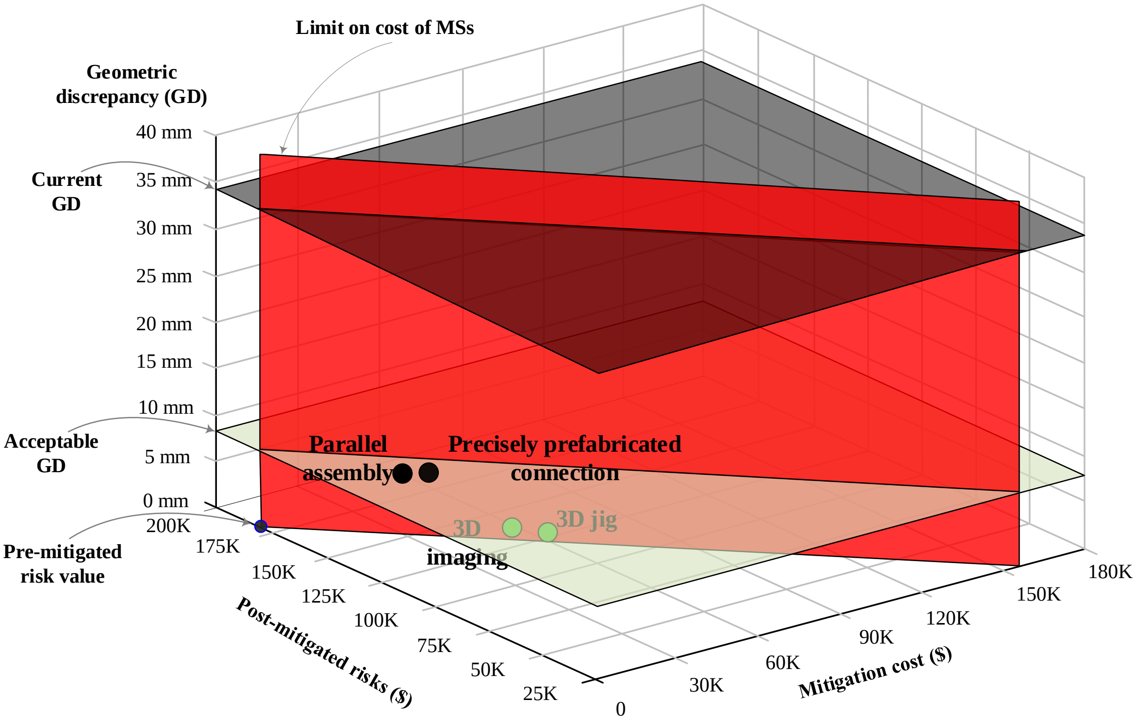
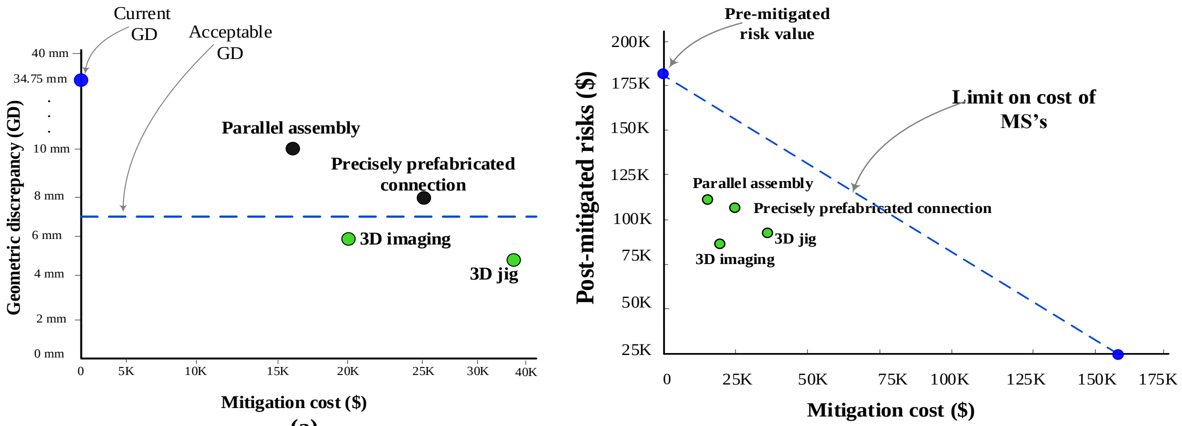


Figure 3.13. 3D graph shows the impact of different MSs on risks and geometric discrepancy.



(a) **(b)**

Figure 3.14. 2D graph show the impact of MSs on: (a) current geometric discrepancy, and (b) pre-mitigated risk value.

The previous assessment of the optimum MS was based on the strict tolerance approach. However, there might be some projects that would benefit from a relaxed tolerance approach. The modular design team may decide to achieve the overall project objectives (cost, quality, time, etc.) by designing modules that are flexible enough to accommodate performance of the required geometric adjustments at job site during erection phase. For example, if adjustable connections (e.g., bolted connection with slotted holes) have been used as a relaxed tolerance mitigation strategy (MS_1) (Table 3.5), there will be an expected geometric discrepancy (EGD) associated with the assembled modules during fabrication, transportation, and erection (Figure 3.15). The EGD, which is typically defined by the design team based on the technical specifications of employed connection, is assumed to be 20 mm. This EGD is usually greater than the acceptable geometric discrepancy (GD) (strict function tolerance limit) that is defined as 6 mm based on construction tolerance standards (BSI, 2011). The EGD due to tolerance relaxation will be overcome at job site to achieve the strict tolerance limit (acceptable geometric discrepancy) (i.e., module geometry will be adjusted at job site to achieve final alignment). On the hand, the EGD due to tolerance relaxation will also affect the modularization scope/extent which should be reduced to prevent damage to non-structural components. The affected modular components that need to be installed at job site are identified as drywall system, steel studs, and insulation layers (Figure 3.15). The total cost of the relaxed tolerance approach using MS_1 (bolted connection with slotted holes) will then be estimated using Equation 2. The total cost of installing bolted connections at the fabrication shop is estimated as \$15,000, using the data provided by the industry partner of the current case study project (e.g., CPM schedule, fabrication and assembly cost codes, and lessons learned documents). The cost of installing shifted modularization scope/extent (drywall systems, insulation layers, and steel studs) at job site during erection phase is evaluated as \$35,000. The cost of adjusting the module geometry to achieve final alignment on site is estimated as \$10,000. Finally, the expected cost of tolerance issues despite these efforts (i.e., the expected risks cost associated with MS_1) is calculated as \$50,000. It should be noted that the previous costs were estimated for the whole project (16 modules). For illustrative purposes, rational assumptions have been made to develop the values of the remaining mitigation strategies in Table 3.5 using other types of adjustable connections (e.g., bolted connections with oversized hole, pin-fuse joints, etc.).

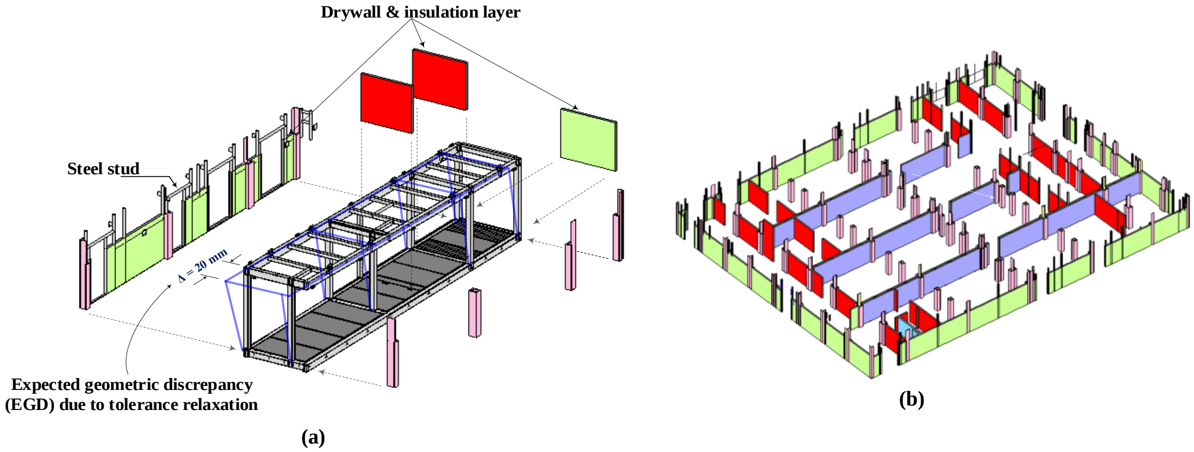


Figure 3.15. Shifted modularization scope/extent from fabrication shop to job site: (a) per module, (b) per project.

Table 3.5. Summary of the impact of different relaxed tolerance MSs on EGD, modularization scope, and post-mitigated risk value.

MS	Cost of MS (C_1)	EGD (mm)	Modularization scope (%)	Cost of installing shifted modularization scope (C_2)	Cost of adjusting module geometry (C_3)	Post-mitigated risk (C_4)
MS_1	\$15k	20	90%	\$35k	\$10k	\$50k
MS_2	\$15k	30	70%	\$45k	\$15k	\$60k
MS_3	\$15k	40	55%	\$50k	\$20k	\$65k
MS_4	\$15k	50	40%	\$60k	\$25k	\$70k

2D and 3D graphs have been developed to demonstrate the impact of relaxed tolerance MSs (Figure 3.16 and Figure 3.17). It should be noted that the mitigation cost is represented as the summation of $\boldsymbol{C_1}$, $\boldsymbol{C_2}$, and $\boldsymbol{C_3}$. Also note that the vertical distance between the EGD and acceptable GD represents the required amount of work to bring the modules into alignment on site, and modularization scope (percentage) is the amount of work performed in the shop. Based on the results for the relaxed approach, MS$_1$ is the optimum mitigation strategy as it has the lowest MS cost (Figure 3.16).

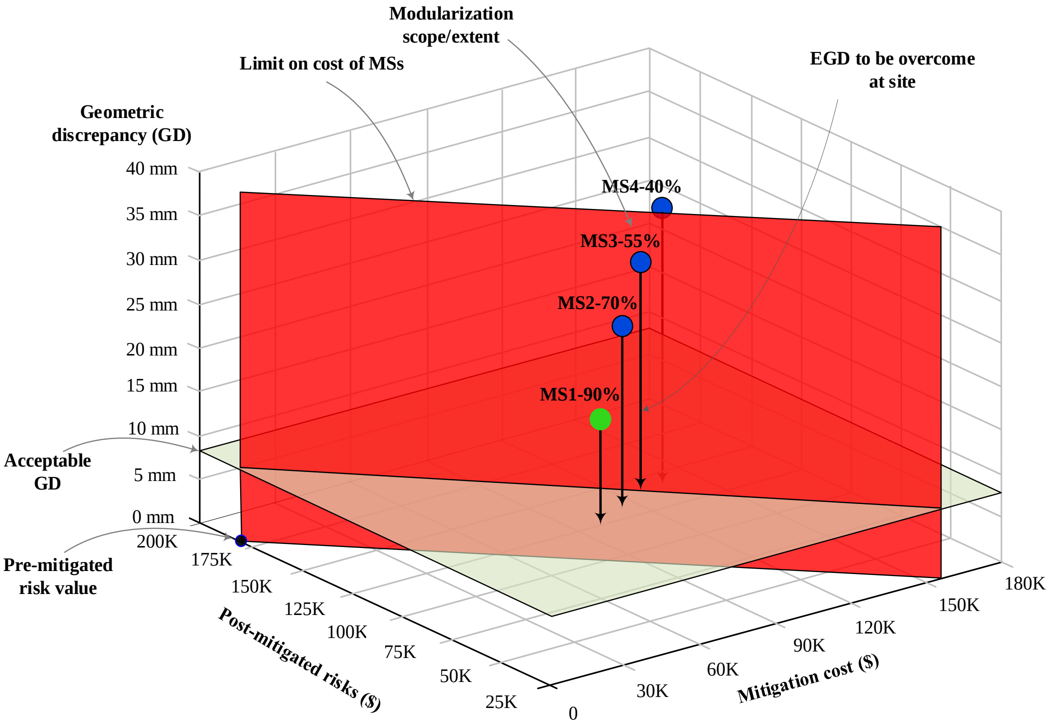
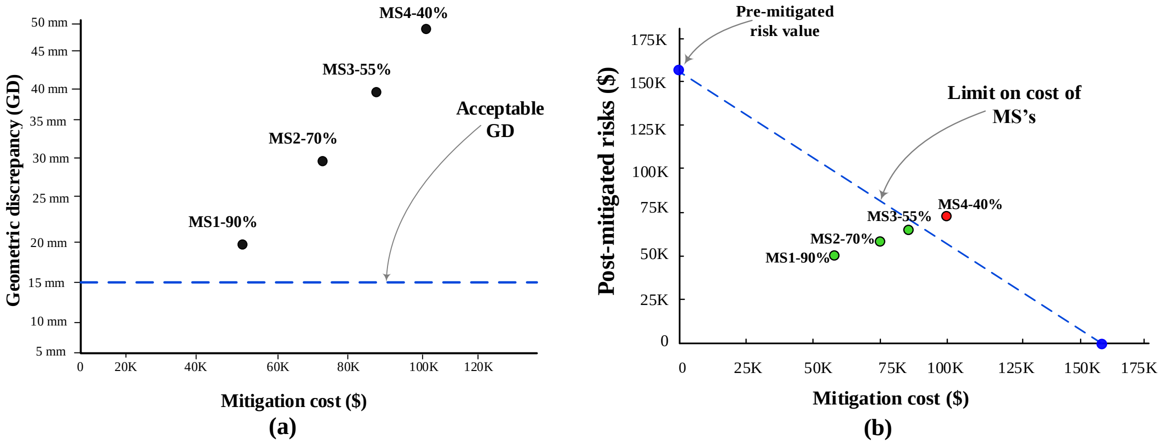


Figure 3.16. 3D graph shows the concept of relaxed tolerance approach.



(a) **(b)**

Figure 3.17. 2D graph shows the impact of different relaxed MSs on: (a) geometric discrepancy, and (b) post-mitigated risk.

Comparing the effectiveness of the optimal MS based on the strict tolerance approach with the optimal MS based the relaxed tolerance approach will help decision makers to choose the best approach for a specific project. The results reveal that there is no significant cost difference between 3D imaging (\$20,000 + \$82,493.12 = \$102,493) and adjustable connections with 90% modularization scope (\$15k + \$35k + \$10k + \$50k = \$110,000), which indicates that concept of relaxed tolerances may be a feasible option for this project.

Sensitivity Analysis

To check how the optimum risk response decisions are sensitive to the estimated input values of tolerance-related risks (probability of occurrence, impact on cost, and impact on schedule), sensitivity analysis is performed. For demonstration purposes, the probability of occurrence of tolerance-related risks will be used to explore the sensitivity of the optimum selection of the proposed mitigation strategies. Two-level of values are defined to estimate the probability of occurrence (in addition to the primary values of the evaluated probabilities as shown in Table 2.2): 1) ***first level***: the probability of occurrent of tolerance-related risks is considered to be 10% of the primary estimated value, and 2) ***second level***: the probability of occurrence of tolerance-related risks is considered to be 10 times of the primary value. Figure 3.18 shows the expected risk profile using different estimations/levels of the probability of occurrence. Table 3.6 shows the optimum risk response decision for the estimated risk profiles after repeating the scenario analysis step, which illustrates how sensitive is the decision of risk management plan to the estimation of the main risk characteristics.

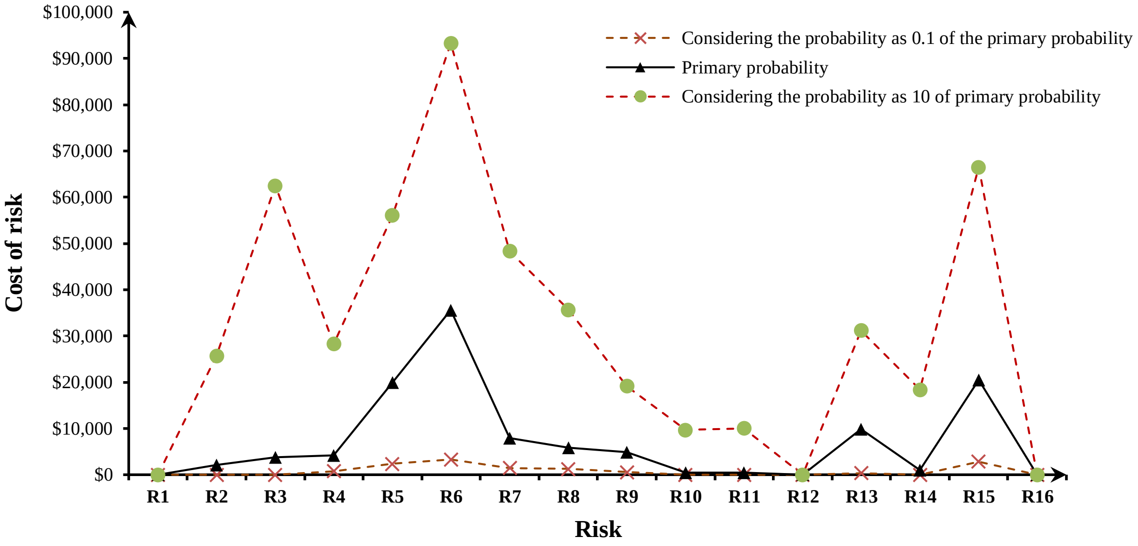


Figure 3.18. Sensitivity analysis results of the tolerance-related risks at three different levels of the probability of occurrence .

Table 3.6. Optimum risk management plan considering different risk profiles.

Risk profile	Optimum risk response decision
- based on the primary probability	3D imaging
- considering the probability as 0.1 of primary probability	None
- considering the probability as 10 of primary probability	3D imaging, 3D jig, precisely prefabricated connections, and parallel assembly

3.4 Conclusions

A risk management framework (RMF) for proactive management of tolerance-related risks and excessive geometric variability issues in modular construction (MC) projects is introduced in this chapter. The developed RMF includes a risk register table for tolerance-related issues and unique modularization risks, a systematic process for evaluating mitigation strategy effectiveness based on tolerance theory, and a structured method for representing the results (using 2D & 3D graphs). The case study presented demonstrates how the developed RMF can be applied in a real MC project. Strict and relaxed tolerance approaches are used in this case study to demonstrate the proposed RMF. The relaxed tolerance approach is introduced as a potential proactive mitigation strategy to achieve functional tolerance requirements with the aim of minimizing the total project cost (i.e., reducing the amount of site-fit rework and schedule delay). This approach identifies the optimal geometric variability (i.e., relaxed tolerances) for a specific project by addressing the trade-off between offsite cost (in the design and fabrication phases) and site-fit cost (during the erection phase). Based on both tolerance approaches (strict and relaxed), different mitigation strategies are identified, analyzed, and assessed to find the optimal solution. The results for the presented case study reveal that optimal mitigation strategy for each tolerance approach have no significant cost difference (less than 7%). This demonstrates that the concept of the relaxed tolerance approach can in some cases be a viable solution and generate the same benefits as the strict tolerance approach.

The primary contributions of the developed RMF are the identification and quantitative evaluation of tolerance-related issues and risks unique to MC projects, the introduction of the relaxed tolerance concept as a proactive solution to improve modularization performance and maximize its benefits, the development of a practical process for evaluating mitigation strategy effectiveness using either the strict or the relaxed tolerance approach, and the provision of an efficient method for optimizing the trade-off between offsite and onsite costs. Also, the current study contributes to the existing engineering and management body of knowledge by proposing an efficient risk management framework, which will support the decision-making process with respect to the optimum selection of mitigation strategies in modular construction projects. It is expected that the primary users and main beneficiaries of the proposed framework will be stakeholders, engineers, and modular construction managers (e.g., designers, fabricators, and contractors) who are involved in a collaborative contractual agreement (e.g., integrated project delivery, design-build, etc.) during the early project phases (i.e., at early detailed design).

Despite demonstrating the applicability of the proposed RMF and the expected benefits of employing the relaxed tolerance approach, some limitations to this study can be identified. The demonstrated relaxed tolerance approach considers hypothetical values for the Mitigation Strategy MS_2, MS_3, and MS_4 based on rational assumptions. The intent of introducing the relaxed tolerance approach is to show the functional form of the proposed evaluative method for assessing and optimizing the trade-offs between offsite costs during design and fabrication and onsite cost during the erection phase, and finding the optimal mitigation strategy. The developed results and graphs are sufficient for this purpose. In addition, confidence in the optimal mitigation action relies heavily on the accuracy of the input data for each risk (probability and expected impact), thoroughness of risk identification, and accuracy of mitigation strategy modelling (expected geometric discrepancy).

Chapter 4

Integrating the Impact of Propagation Behaviour of Excessive Geometric Variabilities in Project Risk Management

4.1 Introduction

This chapter presents a framework for the holistic assessment and efficient management of excessive geometric variability risks in modular construction projects. In the framework presented here, a classical risk assessment technique, in which a probability-impact risk model is employed for evaluating risks individually from a local perspective, is linked with an innovative technique for considering interactions among risks from a global perspective, which employs the concepts of a design structure matrix and pairwise comparisons using the analytical hierarchy process. The results of a case study conducted for validation purposes demonstrate that the developed framework can provide industry practitioners (owners, designers, fabricators, and contractors) with a better understanding of the risk profile for a project as well as new insights into the development of proactive mitigation strategies from both a local and a global perspective.

4.2 Proposed Framework

This section presents the proposed framework (Figure 4.1) for analyzing, modelling, assessing, and managing local and global exposures of tolerance-related risks to support decision making with respect to the optimal selection of mitigation actions in modular construction projects. This framework is composed of five phases: 1) risk identification, 2) local and global risk analysis and assessment, 3) risk modelling and prioritization, 4) scenario analysis, and finally 5) decision making. The application of the proposed framework facilitates evaluating and prioritizing the impact of tolerance-related risks and their unique relationships from local and global perspectives, assessing the effectiveness of mitigation strategies at local and global levels, and representing the results in 2D graphs to support decision making. The next sub-sections explain the details of each phase.

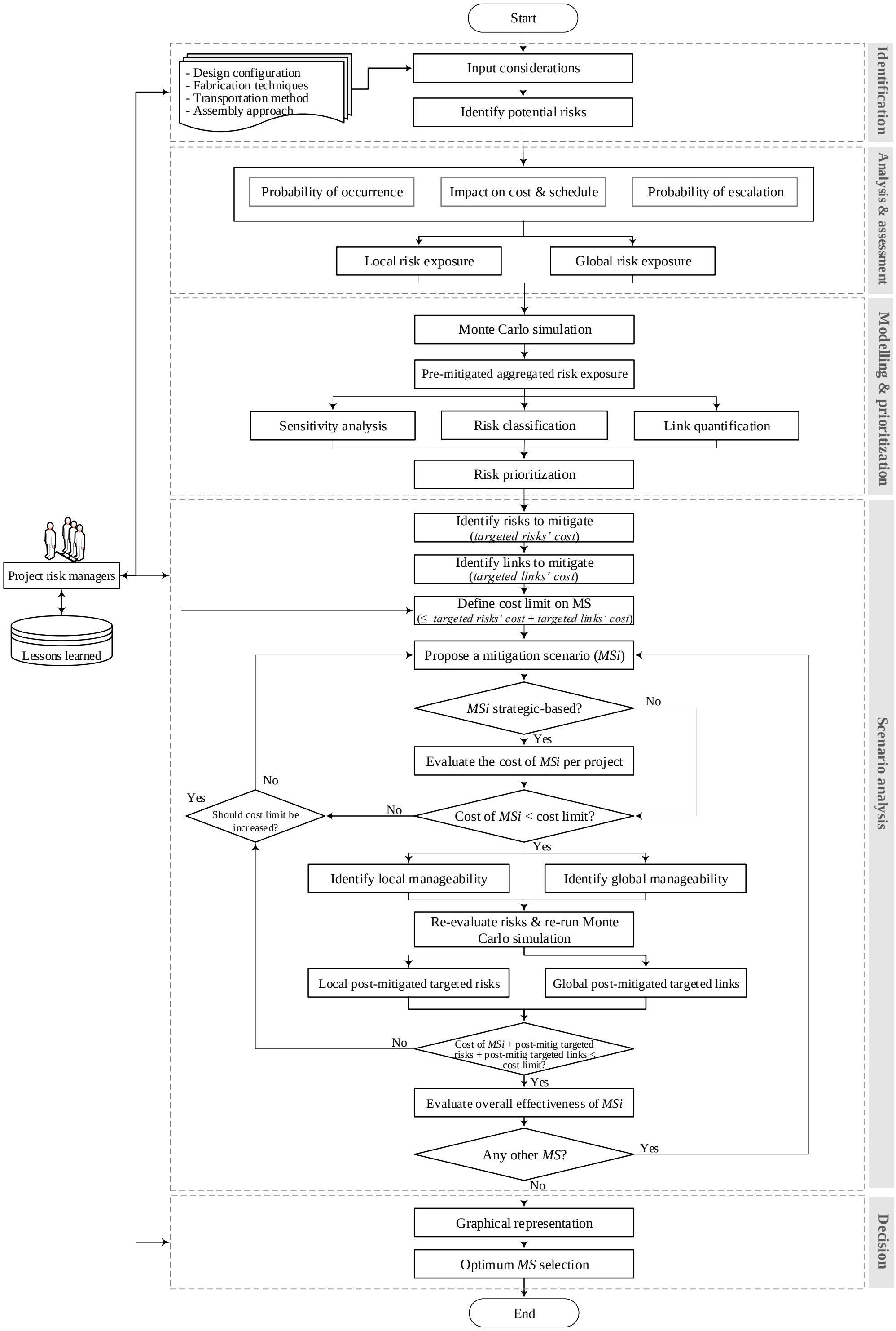


Figure 4.1. The proposed framework to facilitate evaluating and managing the local and global impact of tolerance-related risks in modular construction projects.

4.2.1 Risk Identification

Risk identification is the first step in classical project management, which aims to identify potential risks that might have negative and/or positive effects on the overall objectives of construction projects (ISO, 2009; PMI, 2013). The current research study mainly focuses on the negative impacts of tolerance-related risks in modularized projects. The risk identification process can be carried out using several techniques such as analogy (e.g., checklist, documentation review), heuristic (e.g., subject matter experts, open-ended questions, interviews), and analytic (e.g., scenario analysis) techniques (ISO, 2009; Muriana et al., 2017; Yoe, 2011).

4.2.2 Risk Analysis and Assessment

There are three main risk characteristics that need to be analyzed in this phase: 1) probability of occurrence, 2) probability of escalation, and 3) impact on cost and schedule. The next sub-sections explain the details of evaluating these risk characteristics.

Local risk assessment

The local risk assessment aims to evaluate the probability of occurrence and impact of the identified risks. The probability of occurrence can be defined objectively using historical data or subjectively based on subject matter expert insight. The defined probability can be expressed qualitatively (e.g., very rare, rare, unlikely, etc.) or quantitatively (percentages) (Aven et al., 2009; CII, 2012). The expected impact can also be expressed using either a qualitative approach (e.g., ordinal or cardinal scale), or a quantitative approach (e.g., cost or time impact) (Aven et al., 2009; CII, 2012; ISO, 2009; Olechowski et al., 2016). Using P-I risk model, the local exposure of risk i (LE_i) can be assessed as the product of probability of occurrence (P_i) and potential impact (I_i) (Equation 4-1).

$$LE_i = P_i \times I_i \qquad 4\text{-}1$$

Global Risk Assessment

The global risk assessment aims to evaluate the probability of escalation between related risks, which includes two major steps: 1) identifying the relationships and interactions among risks using the concept of a DSM (i.e., qualitative assessment), and 2) quantifying the relationships via pairwise comparisons using the AHP (i.e., quantitative assessment). The following steps show the estimation process of probability of escalation.

Step (1): Identifying relationship between risks

The relationship between risks is classified into dependent (precedence linkage), independent (no linkage), and interdependent (coupled and mutually dependent linkage) (Karniel & Reich, 2009). The concept of a DSM, which was introduced by Steward (1981a, 1981b), will be used as an effective and practical tool to define the relationships among risks. A DSM is defined as a binary and square matrix where DSM_{ij} is either unity or a marked sign when there is a direct interaction between risks R_i and R_j (i.e., R_i is a consequence of R_j, or R_j is a cause of R_i), otherwise the value of DSM_{ij} is zero or empty. The qualitative assessment of relationships among risks in a binary-DSM can be performed by project risk managers using different techniques such as interviews or the Delphi method. Figure 4.2 shows an example of a binary-DSM and its corresponding risk network.

Risk	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
R1	▨			×				
R2	×	▨	×					
R3	×		▨					×
R4		×		▨	×			
R5	×	×	×		▨			
R6					×	▨		
R7					×		▨	
R8								▨

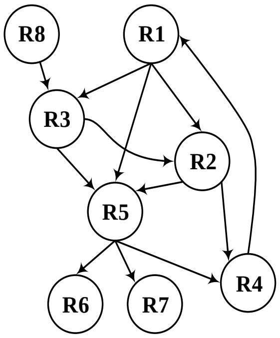


Figure 4.2. Binary-DSM and risk network showing the relationships between risks.

Step (2): Quantifying relationship between risks

Since the binary-DSM only provides qualitative information about risk interactions, Chen & Lin (2003) developed a model to transform the binary-DSM into a numerical-DSM (Figure 4.3) via pairwise comparisons using the AHP method (Saaty, 2003) as follows:

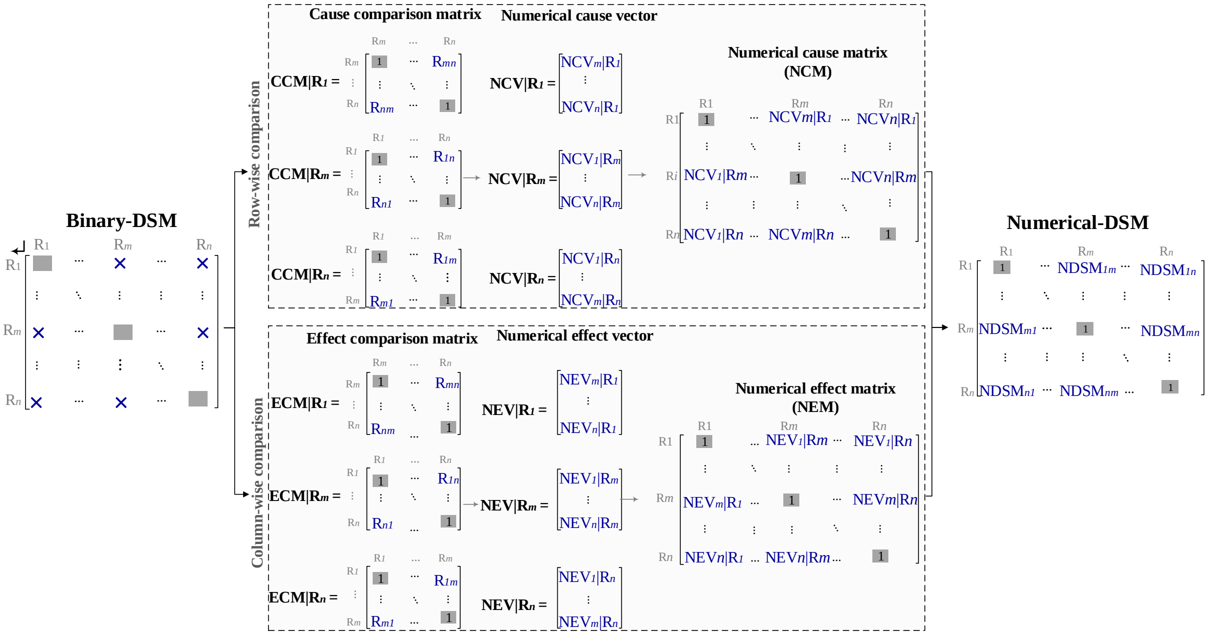


Figure 4.3. Transforming the binary-DSM into a numerical-DSM.

Pairwise comparison: Any non-zero risks in a row of the binary-DSM represents a potential cause (or source) to the risk of that row. Similarly, any non-zero risks in a column of the binary-DSM represent a potential effect (or consequence) from the risk of that column. Therefore, there are two perspectives in assessing the coupling strength between risks in a binary-DSM: 1) row-wise comparison for measuring potential cause relationships, and 2) column-wise comparison for measuring potential effect relationships. This kind of assessment will help project risk managers to avoid any misevaluation issues, which could occur by looking at the risk only from one perspective (e.g., cause-based or effect-based assessment). For each risk R_i in the binary-DSM, all of the non-zero risks other than the diagonal risk in row i and column i will be extracted to form two matrices, namely cause and effect comparison matrices (CCM|R_i and ECM|R_i), where risk R_i will serve as a criterion to evaluate the coupling strength for the risks in both matrices. Pairwise comparison using the AHP is used to evaluate the coupling strength using a cardinal comparison scale that ranges from equally important to extremely important (i.e., from 1 to 9) (Saaty, 2003). In the cause comparison matrix, risk R_i in row *i* will serve as a criterion for all non-zero risks in row *i*. For every pair of risks compared, project risk managers will numerically assess, using the cardinal comparison scale, which risk is more important as a cause (source) in terms of probability of escalation to risk R_i (i.e., which risk is more important in triggering R_i). Likewise, in the effect comparison matrix, risk R_i in column *i* will serve as a criterion for all non-zero risks in column *i*. For every pair of risks compared, project risk managers will numerically assess, using the cardinal comparison scale, which risk is more important as an effect (consequence) in terms of probability of escalation from R_i.

Evaluating the Eigen-function: In order to measure the relative coupling strength between risks, an eigen-vector (priority vector) is estimated for each of the cause and effect comparison matrices formulated in the last step. The priority vector represents the ranking of each risk in the cause and effect comparison matrices. The consistency of the estimated priority vectors should be tested by calculating the consistency index using the AHP (Saaty, 2003). For an $n \times n$ cause comparison matrix, there are *n* eigen-vectors, which will form a numerical cause vector with respect to R_i (NCV|R_i). Each value in the numerical cause vector will be placed back to its original location in the binary-DSM to form the numerical cause matrix (NCM). In the same way, a numerical effect vector (NEV|R_i) and a numerical effect matrix (NEM) can be generated.

Numerical-DSM: The calculated numerical cause matrix based on row-wise comparison and numerical effect matrix based on column-wise comparison will be combined using geometrical averaging (Equation 4-2) to formulate the numerical-DSM (NDSM), which represents the overall coupling strength between risks.

$$NDSM_{ij} = \sqrt{NCM_{ij} \times NEM_{ij}} \qquad \text{4-2}$$

where $0 \leq NDSM_{ij} \leq 1 \quad (i, j = 1, 2, \ldots, n)$.

The numerical value of coupling strength ($NDSM_{ij}$) between related risks is interpreted as probability of escalation. The global exposure of risk i is then estimated as the product of probability of occurrence of risk i, probability of escalation from risk i to the triggered risk, and impact of the triggered risk (Equation 4-3).

$$GE_i = P_i \times \sum_{j=1}^{n} P_{ij} \times I_j \qquad \text{4-3}$$

where GE_i is the global exposure of risk i, P_i is the probability of occurrence of risk i (source risk), P_{ij} is the probability of escalation of risk j originating from risk i, and I_j is the impact of triggered risk j. The aggregated exposure of risk i (AE_i) can then be estimated as the summation of local and global exposures (Equation 4-4).

$$AE_i = LE_i + GE_i \qquad \text{4-4}$$

4.2.3 Risk Modelling and Prioritization

In the previous step, tolerance-related risks have been deterministically assessed locally and globally through single-point estimate of the potential impact. In this step, probabilistic risk assessment techniques (e.g., Monte Carlo simulation) will be used to evaluate the potential risk exposure. Based on sensitivity analysis results obtained by Monte Carlo simulation, risks will be ranked based on their impact for mitigation purposes. On the other hand, from a global perspective, risks can be classified into three categories based on the information in the binary-DSM: 1) source: risks with no predecessors, but lead to many risks, 2) transitive: risks with predecessors and lead to others, and 3) accumulative: risks with many predecessors and no successors (Kreimeyer & Lindemann, 2011). This classification provides a new insight into risks and their roles so that project risk managers can focus their efforts on mitigating the source and transitive risks that could lead to many other risks. In addition, the link between risks can be quantified as the product of probability of escalation and impact of the triggered risk. The results of link quantification will provide a better understanding of the consequences of the propagation behaviour and support risk managers to develop efficient mitigation strategies to manage global risk exposure by targeting the high-impact links.

4.2.4 Scenario Analysis

Based on the results of the sensitivity analysis by Monte Carlo simulation, risk classification, and link quantification in the last step, risks with high impact will identified and targeted for mitigation purposes. The proposed mitigation strategies should cost less than a cost limit. In classical project risk management, the cost limit on mitigation strategies is usually defined as the value of the pre-mitigated targeted risks. However, including the global risk exposures in the risk assessment process will provide a logical justification to relax this MS cost limit by including both local and global risk exposure (Equation 4-5).

$$\begin{aligned} MS\ cost\ limit\ \leq\ & cost\ of\ \ pre\ mitigated\ targeted\ risks \\ &+\ cost\ of\ pre\ mitigated\ targeted\ links \end{aligned} \tag{4-5}$$

4.2.5 Risk Response Decision

Based on the results of the previous step, the pre-mitigated risk, post-mitigated risk, and the costs of candidate mitigation strategies will be represented in 2D graphs to support decision making with respect to the selection of optimal mitigation actions. The developed framework described in this section is generic and can be applied to a range of modular construction projects. In order to further describe and demonstrate the framework, it is applied to a case study in the following section.

4.3 Case Study

The case study investigated in this chapter relates to a one-storey modular data centre project comprised of 16 modules (Figure 4.4). The purpose of the case study is to demonstrate the proposed framework (Figure 4.1). This case study comes from a recent project where numerous interrelated risks (tolerance-related problems) have been experienced during the erection phase onsite (Figure 4.5), resulting in misalignments between modules, site-fit rework, and schedule delay issues.

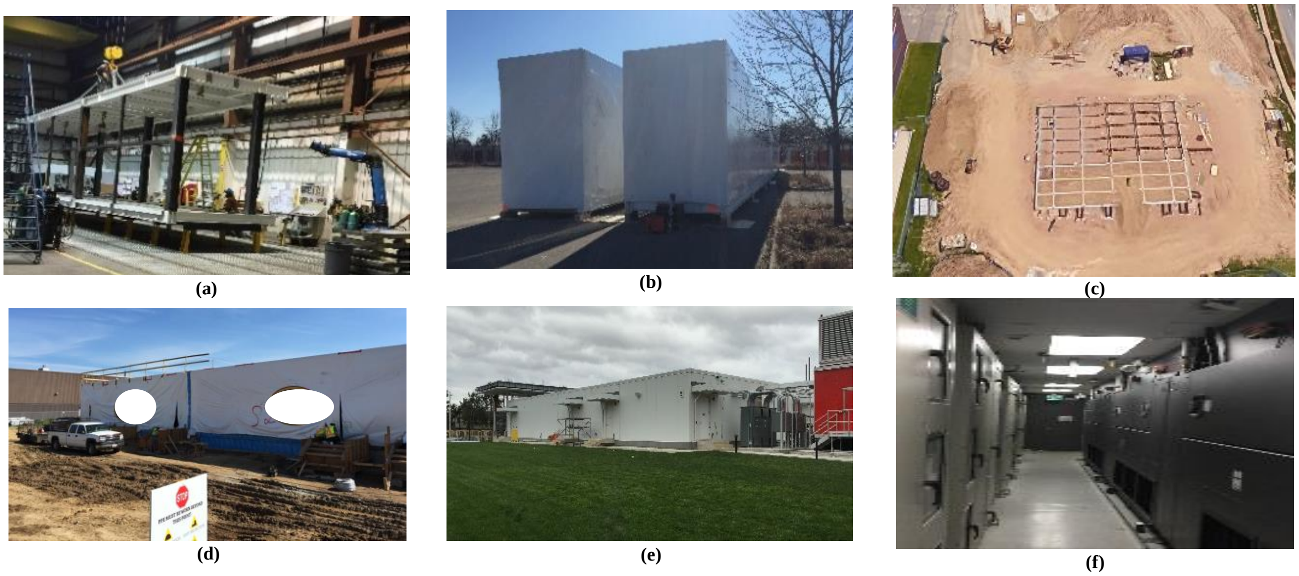

(a) (b) (c)
(d) (e) (f)

Figure 4.4. The main case study project during: (a) fabrication and assembly processes, (b) temporary storage area, (c) site preparation and building concrete foundations, (d) erection phase, (e) completed building from outside, and (f) finished structure from inside.

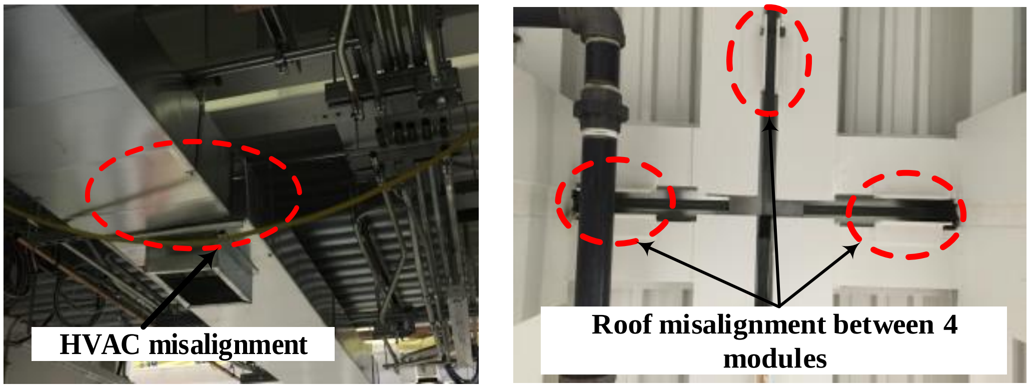


Figure 4.5. Misalignment issues between modules during erection phase onsite.

4.3.1 Risk Identification

Table 4.1 summarizes the main tolerance-related risks that might be encountered in modular construction projects. These risks have been identified and refined based on several face-to-face meetings with the industry partner of this research (fabrication team), meetings with the site-installation and erection company responsible for onsite works, and a literature review. It should be noted that the current research study approaches the identified risks from a modular perspective (i.e., risks due to either tolerance-related issues, or uniqueness of modularization processes).

Table 4.1. Risk register table for tolerance-related issues and unique modularization risks.

Risk ID	Risk name	Category of impact	
		Schedule	Cost
R1	Unclear design documents	Delay	Extra cost
R2	Errors in design documents	Delay	Extra cost
R3	Late design changes	Delay	Extra cost
R4	Welding defects	Delay	Extra cost
R5	Weather-proofing shroud has defects	Delay	Extra cost
R6	Sub-Assemblies (parts) have excessive geometric variation	Delay	Extra cost
R7	Non-volumetric units (frames) have excessive geometric variation	Delay	Extra cost
R8	Volumetric unit (module) has excessive geometric variation	Delay	Extra cost
R9	Foundations have excessive geometric variation	Delay	Extra cost
R10	Bad weather condition at site	Delay	Extra cost
R11	Increased working hours due to rework increase accidents	Delay	Extra cost
R12	Module has non-structural damages	Delay	Extra cost
R13	Module has a structural damage	Delay	Extra cost
R14	Module-to-module alignment time is increased	Delay	Extra cost
R15	Module-to-site alignment time is increased	Delay	Extra cost
R16	Mechanical, electrical, plumbing (MEP) fit-up time is increased	Delay	Extra cost
R17	Lack of tolerance-based QC checks (technology)	Delay	Extra cost
R18	Fabrication errors	Delay	Extra cost
R19	Inefficient use of fabrication and assembly equipments	Delay	Extra cost

4.3.2 Risk Analysis and Assessment

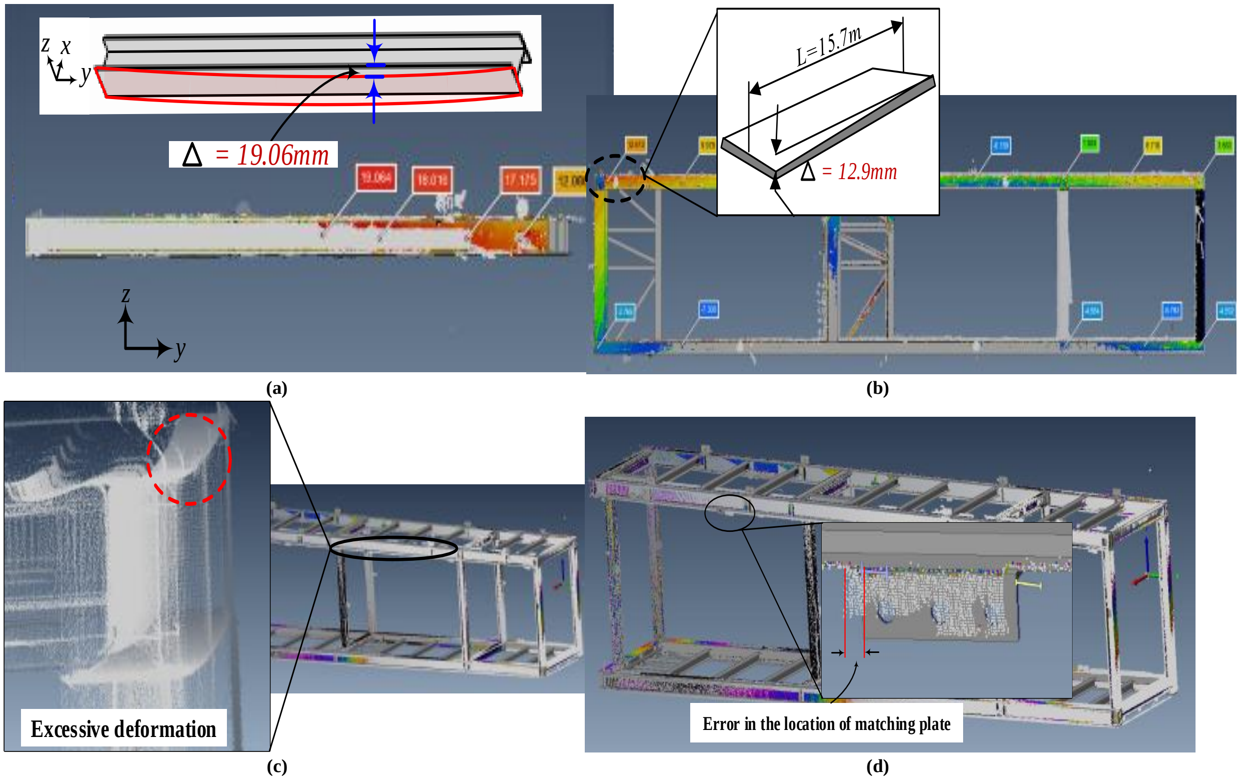
The next step of risk identification (qualitative risk assessment) is to analyze the main risk characteristics (probability of occurrence, probability of escalation, and potential impact) in order to evaluate the local and global risk exposures.

Local risk assessment

In this step, a quantitative approach will be used to represent the probability of occurrence as a percentage and impact as added time and/or cost. The analysis of the main risk characteristics at the local level was performed based on: 1) available information from the case study (e.g., CPM schedule), 2) previous lessons learned documents provided by industry partner, 3) rational assumptions based on meetings and observations during fabrication and erection phases of current case study, and 4) available information from the literature (CII, 2001, 2005; COAA, 2003; RSMeans, 2012).

For some of the registered risks (e.g., R_6, R_7, and R_8), deviation analyses (which compares the as-built and as-designed states) have been used to evaluate the main risk characteristics. As-built data for the main structure of one of the modules was collected using a FARO LS 840HE laser scanner during the assembly process at the fabrication shop (Figure 4.6), and as-designed data was extracted from a building information model (BIM). The commercial software PolyWorks® was used to perform deviation analysis. Based on the results of comparing the geometric and dimensional variabilities of current modular components, with the acceptable tolerance limits dictated by standards (BSI, 2011), it was found that the main structure of the module had the following out-of-tolerances: ***Parts***: 2 columns out of 8 have bowing issues, 1 column out of 8 has length issues; ***frames***: 3 frames out 8 had excessive geometric variability; and ***module***: in the overall assembled module 5 columns out of 8 were out-of-plumb, 3 matching (connection) plates out of 7 were out-of-tolerance, and 1 roof frame beam out of 4 has excessive deformation (Figure 4.7). Based on these measurements, the probability of out-of-tolerance is estimated as the geometric average as: 17.6% for parts, 37.5% for frames, and 40.6% for modules (Table 4.2).

Figure 4.6. As-built data collection using laser scanning technology during assembly process at the fabrication shop.



(a) (b)

(c) (d)

Figure 4.7. Results of deviation analysis: (a) bow in column, (b) flatness of floor frame, (c) deformation in roof frame, and (d) location of matching plates.

Table 4.2 summarizes the values assigned to the probability of occurrence and the potential impact range with respect to cost and schedule for each risk. Due to a lack in the information needed to generate optimistic and pessimistic values for impacts, rational assumptions were made to develop these values for the purpose of demonstrating the application of the proposed framework. It should be noted that the impacts on cost and schedule were estimated on a per volumetric module basis.

Table 4.2. Probability of occurrence and impact ranges of the registered risks.

Risk	Probability (%)	Impact					
		Schedule (days)			Cost ($)		
		Min	Most likely	Max	Min	Most likely	Max
R1	0.80^{5}	0.85	1.06^{2}	1.30	220	270^{5}	330
R2	5.40^{5}	0.50	0.62^{2}	0.80	250	320^{5}	380
R3	10.00^{5}	0.50	0.62^{2}	0.80	1,980	$2{,}470^{5}$	2,970
R4	18.80^{1}	0.60	$0.75^{1\&2}$	1.00	920	$1{,}140^{4\&6}$	1,600
R5	16.60^{1}	0.52	$0.66^{1\&2}$	0.93	500	$620^{4\&6}$	870
R6	17.70^{3}	0.35	0.37^{2}	0.6	620	$650^{4\&6}$	1,030
R7	37.50^{3}	0.82	0.86^{2}	1.42	940	$990^{4\&6}$	1,90
R8	40.60^{3}	1.14	1.20^{2}	1.92	2,060	$2{,}170^{4\&6}$	3,470
R9	31.30^{1}	0.20	0.25^{1}	0.35	440	$550^{1\&4}$	770
R10	4.60^{1}	0.15	$0.18^{1\&2}$	0.26	150	$190^{4\&6}$	270
R11	0.15^{4}	1.51	1.68^{4}	2.85	3,430	$3{,}810^{5}$	6,480
R12	5.40^{1}	0.08	0.11^{1}	0.15	290	370^{1}	510
R13	0.01^{5}	4.80	6.01^{1}	8.40	4,500	$5{,}000^{1}$	7,500
R14	37.50^{1}	0.12	0.13^{1}	0.19	1,040	$1{,}340^{1\&2}$	2,010
R15	12.50^{1}	0.10	0.12^{1}	0.17	550	$720^{1\&2}$	1,080
R16	31.30^{1}	1.08	1.20^{1}	1.80	810	$1{,}020^{1\&2}$	1,530
R17	17.70^{5}	1.41	2.12^{5}	3.10	2,150	$2{,}690^{5}$	4,030
R18	3.70^{1}	0.82	1.20^{1}	1.96	510	640^{1}	1,140
R19	18.30^{5}	0.73	1.15^{5}	1.80	840	$1{,}050^{5}$	1,570

1. Rational assumption based on face-to-face meetings, observations, and site visits with industry partner during fabrication and erection phases
2. Available data of current case study (e.g., CPM schedule)
3. Deviation analysis using laser scanning technology
4. CII: Construction industry institute (CII, 2001, 2005)
5. COAA: Construction Owners Association of Alberta (COAA, 2003)
6. RS cost Data (RSMeans, 2012)

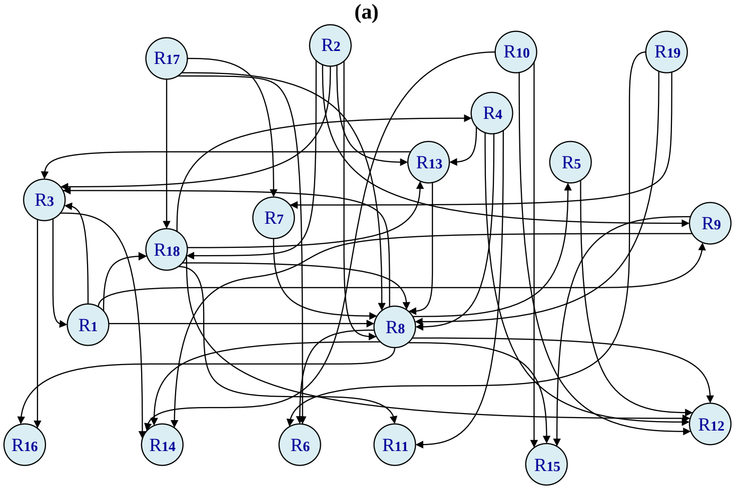
Global risk assessment

In this step, the probability of escalation will be evaluated by assessing the direct cause-effect relationships among registered risks. The concept of a DSM is applied to identify the interactions between risks (i.e., building the binary-DSM). The interactions between risks have been rationally defined based on several meetings with the fabrication team (director of risk control, project managers, modular designers, and plant manager) and erection team (site manager and superintendents). Figure 4.8 shows the results of the risk interaction identification. For instance, from a cause perspective, the potential sources of Risk R_7 (frames have excessive geometric variation) are identified as R_{17} (Non-volumetric units, frames, have excessive geometric variation) and R_{19} (in-efficient use of fabrication and assembly equipment). From an effect perspective, R_8 (volumetric unit, module, has excessive geometric variation) is identified as a potential consequence of R_7. Defining the interactions between risks in the binary-DSM (Figure 4.8.a) allows the project risk manager to visualize the structure of the project risk network (Figure 4.8.b).

Cause

Effect ↲	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
R1			1																
R2																			
R3	1	1						1					1						
R4																		1	
R5								1											
R6								1									1		1
R7																	1		1
R8	1	1		1			1						1				1	1	1
R9	1	1																	
R10																			
R11				1														1	
R12				1	1			1		1								1	
R13		1		1														1	
R14			1					1	1	1									
R15								1	1	1									
R16			1					1											
R17																			
R18	1	1															1		
R19																			

(a)



(b)

Figure 4.8. Interactions among risks in the form of: (a) binary-DSM and (b) project risk network.

Pairwise comparison using the AHP method is then applied to transfer the qualitative information in the binary-DSM into quantitative measures as described in Section 4.2.2. For every pair of risks, project risk managers will numerically assess the potential cause-effect relationship using a cardinal comparison scale that reflects the relative importance (strength) between risks. In this case study, rational assumptions have been made to develop the values of relative importance between risks, based on the meetings with offsite and onsite project team members. The Eigen-vector, which represents coupling strength between risks, is then calculated for each of the cause and effect comparison matrices. The numerical cause and effect matrices (Figure 4.9 and Figure 4.10) are then combined to obtain a full-scaled numerical-DSM that shows the complete information of risk interactions in a quantitative manner (Figure 4.11). The interpretation of the aggregated numerical-DSM is the same as the binary-DSM, except that now the binary-based interactions have been replaced with numerical-based measures with various degrees of probability of escalation. For example, in Figure 4.11, $R_{87} = 0.416$ means that there is a 41.6% chance that R_7 will lead to R_8.

↲	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
R1			1																
R2																			
R3	0.045	0.253						0.111					0.591						
R4																		1	
R5								1											
R6								0.106									0.699		0.193
R7																	0.333		0.667
R8	0.024	0.047		0.081			0.173						0.298				0.157	0.071	0.145
R9	0.750	0.250																	
R10																			
R11				0.800														0.200	
R12				0.209	0.091			0.549		0.088								0.061	
R13		0.174		0.632														0.192	
R14			0.133					0.581	0.152	0.133									
R15								0.479	0.405	0.114									
R16			0.250					0.750											
R17																			
R18	0.090	0.353															0.555		
R19																			

Figure 4.9. The Numerical Cause Matrix (NCM).

↵	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
R1			0.079																
R2																			
R3	0.447	0.428						0.094					0.200						
R4																		0.109	
R5								0.026											
R6								0.050									0.103		0.186
R7																	0.093		0.157
R8	0.267	0.131		0.524			1						0.800				0.645	0.384	0.655
R9	0.128	0.061																	
R10																			
R11				0.119														0.071	
R12				0.161	1			0.205		0.548								0.043	
R13		0.331		0.194														0.390	
R14			0.655					0.204	0.225	0.240									
R15								0.213	0.667	0.210									
R16			0.264					0.169											
R17																			
R18	0.156	0.048															0.157		
R19																			

Figure 4.10. The Numerical Effect Matrix (NEM).

↵	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
R1			0.282																
R2																			
R3	0.143	0.330						0.103					0.343						
R4																		0.331	
R5								0.161											
R6								0.073									0.269		0.190
R7																	0.167		0.324
R8	0.081	0.079		0.206			0.416						0.489				0.318	0.166	0.309
R9	0.311	0.124																	
R10																			
R11				0.309														0.120	
R12				0.184	0.302			0.336		0.220								0.052	
R13		0.241		0.351														0.274	
R14			0.295					0.374	0.225	0.179									
R15								0.320	0.520	0.156									
R16			0.257					0.357											
R17																			
R18	0.119	0.131															0.296		
R19																			

Figure 4.11. The aggregated numerical design structure matrix.

4.3.3 Risk Modelling and Prioritization

After evaluating the main risk characteristics (probability of occurrence, probability of escalation, and impact ranges), a probabilistic risk assessment technique (Monte Carlo simulation) is applied for risk modelling purposes. The *@Risk*® software from *Palisade* is used as a platform to perform the Monte Carlo analysis. A triangular distribution is used to represent the impact ranges, due to lack of available data to perform distribution fitting techniques (i.e., goodness-of-fit tests). The results of the Monte Carlo analysis after 10,000 iterations at the 80% confidence level (i.e., 80th percentile) revealed that the total expected risk impact on the project (16 modules) is \$153,701 at the local level and \$430,458 at the global level (Figure 4.12). It should be noted the estimated local exposure of tolerance-related risks in this chapter (\$153,701) is lower than the estimated value in Chapter 3 (\$177,952), due to the difference in the representation of the probability of occurrence of the risks in the Monte Carlo analysis. In Chapter 3, the probability of occurrence is applicable for one volumetric module, and thus the estimated risk impact will be based on a volumetric module. To evaluate the risk impact on the overall all project performance, the local impact for a volumetric module is multiplied by total number of modules in RICC Project (16 modules). However, in this chapter, the probability of occurrence is represented for the whole project (16 modules) using a Binomial distribution function.

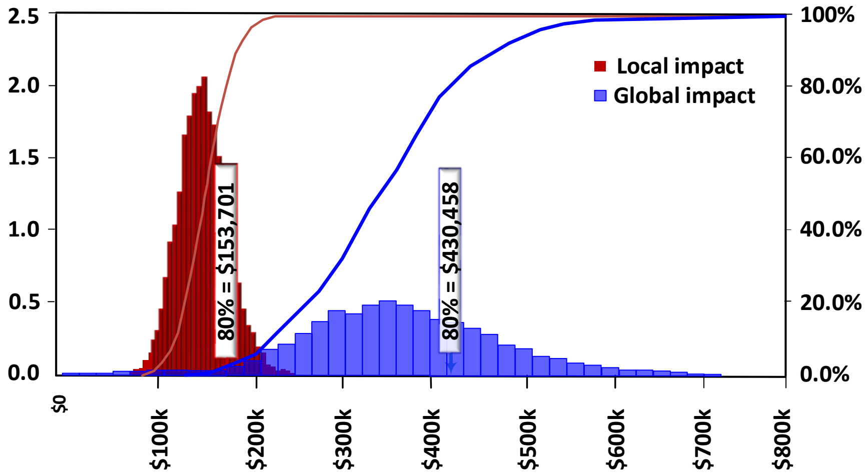


Figure 4.12. Total expected cost of local and global risks exposure.

Figure 4.12 shows the potential risk impact based on different risk assessment techniques. Using the sensitivity analysis results from the Monte Carlo simulation, risks are prioritized locally and globally based on their exposures (Table 4.3). From the local perspective, the gap between expected risk impacts based on deterministic and stochastic risk assessment techniques is wide, due to the random selection process of the simulation algorithm used in the Monte Carlo analysis and extracting the results at a high confidence level (i.e., 80th percentile). Although there is a difference between potential risk impacts based on both assessment techniques at the local level, some of the registered risks (e.g., R_8, R_{16}, and R_{17}) still have high ranks based on both results.

From the global perspective, the ranking and exposure of the registered risks can be changed (increased/decreased) once the propagation behaviour impact is included in the risk assessment process. Based on the results of global risk assessment, some risks (e.g., R_8 and R_{17}) are confirmed to have high rank and exposure. However, other risks (e.g., R_2, R_{10} R_{18} and R_{19}), which are underestimated by local risk assessment, are highlighted to have high rank and exposure from the global perspective. The underestimation of the new highlighted risks from the global perspective is due to disregarding the impact of escalation phenomena and interactions between risks in the assessment process at the local level. Moreover, some risks (e.g., R_6 and R_{16}) have zero impact at the global level, because they are accumulative risks (i.e., will not trigger any other risks), though their impact at the local level are still considerable.

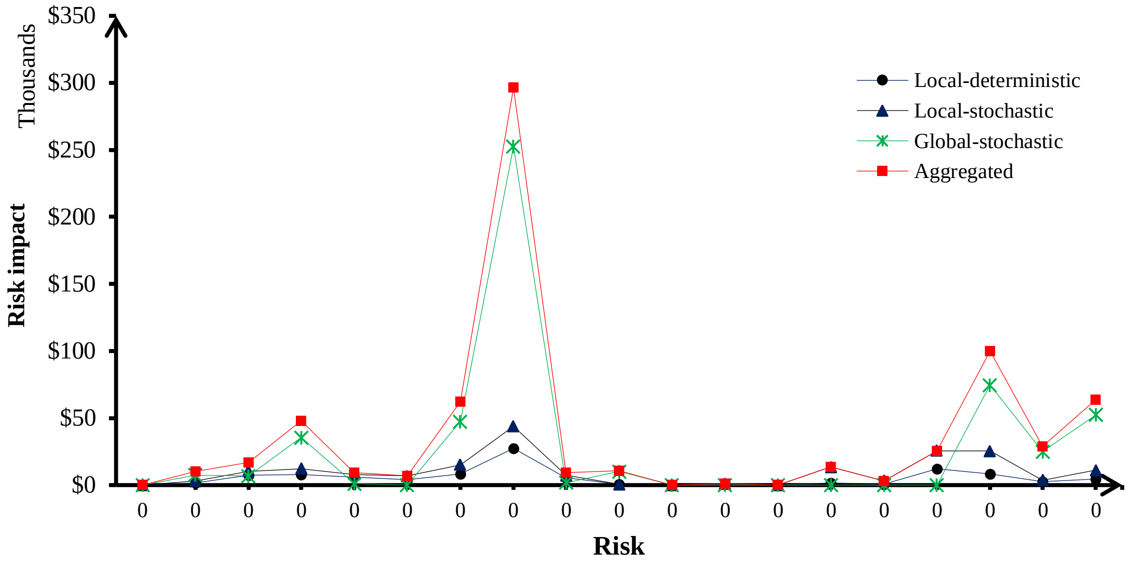


Figure 4.13. The potential risk cost on the whole project (16 modules) based on different risk assessment techniques.

Table 4.3. Ranking of registered risks based on different risk assessment techniques.

Rank	**Local**				**Global**		**Aggregated**$^{1+2}$	
	Deterministic		**Stochastic**^{1}		**Stochastic**^{2}			
1	R8	$27,384	R8	$44,206	R8	$252,599	R8	$296,453
2	R16	$12,000	R17	$25,836	R17	$74,677	R17	$100,180
3	R17	$8,480	R16	$25,271	R19	$52,482	R19	$63,565
4	R7	$8,129	R7	$15,055	R7	$47,334	R7	$62,406
5	R4	$7,920	R14	$13,570	R4	$35,534	R4	$47,718
6	R3	$7,440	R4	$12,073	R18	$24,910	R18	$28,699
7	R5	$5,810	R19	$11,064	R10	$10,083	R16	$25,607
8	R9	$5,250	R3	$10,211	R2	$7,613	R3	$17,093
9	R19	$4,600	R5	$8,019	R3	$6,705	R14	$13,498
10	R6	$4,185	R9	$7,370	R9	$1,794	R10	$10,754
11	R18	$2,400	R6	$6,784	R5	$1,163	R2	$10,465
12	R14	$1,584	R18	$3,735	R1	$0	R5	$9,165
13	R2	$1,564	R15	$3,249	R11	$0	R9	$9,125
14	R12	$576	R2	$2,810	R12	$0	R6	$6,807
15	R10	$562	R12	$1,072	R13	$0	R15	$3,280
16	R15	$460	R10	$670	R14	$0	R12	$1,073
17	R1	$0	R1	$0	R15	$0	R1	$0
18	R11	$0	R11	$0	R16	$0	R11	$0
19	R13	$0	R13	$0	R6	$0	R13	$0

Based on the available information in the binary-DSM, risks are classified into source, transitive, and accumulative (Figure 4.14). This classification can give a new insight into risks and their roles so that project risk managers can focus their efforts on managing the highly interacted risks that might result in other risks. For some of the registered risks, the results obtained from the risk classification approach agree well with the results obtained from the local and global risk assessment techniques. For instance, in Figure 4.14, R_{17} and R_{19} are classified as source risks as well as having high rank and exposure based on local and global risk assessment (Table 4.3). Also, Risk R_8 is classified as transitive risks with a high number of inputs (causes) and outputs (effects), and it has high rank and exposure at local and global levels. The highly interconnected transitive risks (e.g., R_8) can be considered as "hubs" in the risk structure network, which play an important role in the propagation behaviour. Moreover, Risk R_{16} is classified as an accumulative risk (i.e., it has zero impact from global perspective), though it has a considerable impact from local perspective. Therefore, the results of the risk classification technique can provide complementary information about interactions among risks in the risk structure network.

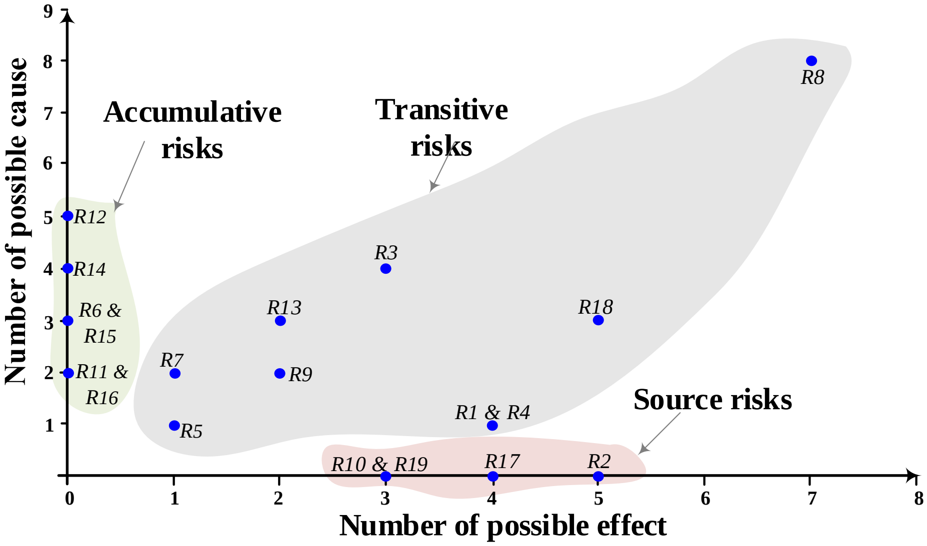


Figure 4.14. Risk classification based on the information in the binary-DSM.

Although the risk classification technique provides a visual representation and useful information about the interactions of risks and their roles, it is still based on qualitative information and does not provide quantitative measures to identify the important links/interactions, so project risk managers can efficiently plan for mitigation actions. Therefore, the impact of each link is quantified as the product of probability of escalation and impact of the triggered risk. The impact values are then grouped using a classification scheme (Table 4.4) , which is developed based on the legacy of the industry partner's risk management approach for the main case study project (RICC-Mississauga), and represented in the colour coded risk structure network (Figure 4.15). The results of link quantification will provide a new insight about the important links that should be targeted in order to manage propagation behaviour.

Table 4.4. Classification scheme of the links between risks.

Impact description	Impact range ($)
Very low	$I < 8,623$
Low	$8,623 < I < 23,634$
Medium	$23,634 < I < 44,314$
High	$44,314 < I < 88,628$
Very high	$I > 88,628$

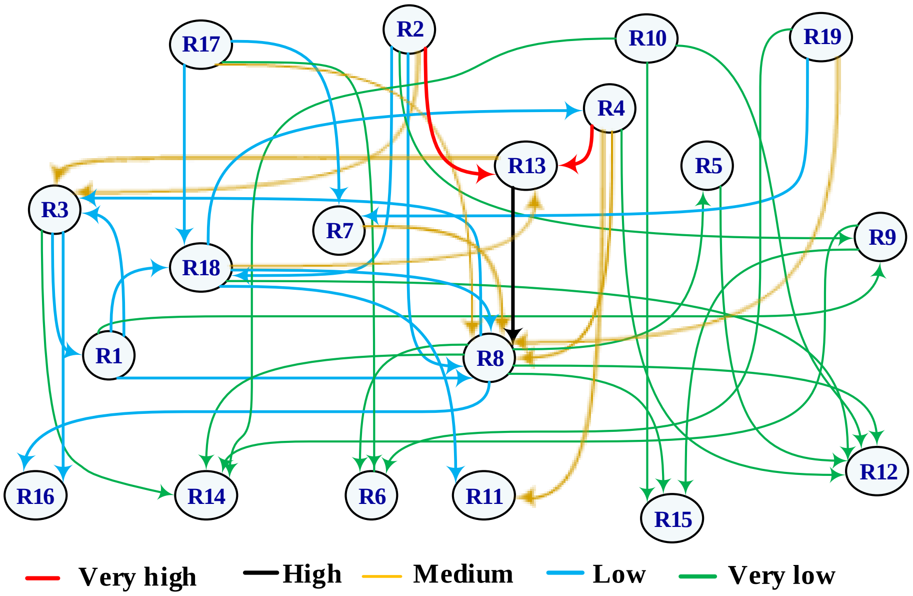


Figure 4.15. Classification of links between risks based on their impact.

4.3.4 Scenario Analysis

Identifying the gap between risk impacts based on different risk assessment techniques is important in estimating the requisite contingency reserve to provide the desired amount of certainty with respect to avoiding schedule delays and cost overruns. Prioritizing risks based on different assessment approaches can lead to a more holistic understanding of risk impact when decisions are made about which risk to target for mitigation. Using available information in a binary DSM to classify risks based on their roles can offer a fresh view of risk interactions in a risk structure network. Quantifying the links between risks can provide additional information about important interactions that should be targeted in order to manage propagation behaviour.

Based on the results of the previous step, Risks R_4, R_7, R_8, R_{16}, R_{17}, and R_{19} will be targeted for mitigation purposes as they have high rank and exposure from local and global perspectives. The risk mitigation approach will be based on reducing two main characteristics: 1) probability of occurrence of targeted risks (local mitigation), and 2) probability of escalation of the links with high impact connecting targeted risks with other related risks (global mitigation). The cost of the proposed mitigation strategy (MS) should not exceed the cost limit, which is defined based on the expected risk impact (Equation 4-5).

From a local management perspective, the cost limit on MSs is defined as the value of the pre-mitigated targeted risks based on the results of stochastic risk assessment at local level ($133,506) (Table 4.3). The proposed MSs, the goal of which is to reduce the probability of the occurrence of targeted risks, are classified as either strategic, in that they can be applied in multiple projects (e.g., 3D imaging and 3D jigs), or tactical, in that it is only intended they be applied in one project (e.g., precisely prefabricated connections and prototyping). Table 4.5 summarizes the cost of each MS per project as well as the effectiveness (manageability) of mitigation actions with respect to the registered risks. The effectiveness (manageability percentage) of candidate MSs can be evaluated based on either objective data (e.g., technical specifications of MSs) or subjective data (e.g., opinions of SMEs). Equation 4-6 shows how MS effectiveness can be estimated using objective data. The expected geometric discrepancy (EGD) represents the suitability of the proposed MS for achieving strict functional tolerances, and the current geometric discrepancy (CGD) represents the overall geometric deviation of the assembled module using current fabrication tools and assembly equipment in the fabrication shop.

$$Effectiveness\ of\ MS = \frac{CGD - EGD}{CGD} \times 100\% \qquad 4\text{-}6$$

It should be noted that the initial cost and effectiveness (manageability) of 3D imaging and 3D jigs are evaluated based on the available information and technical specifications for each MS using Equation 4-6 and that the development of the values for the remaining MSs is derived from rational assumptions.

Table 4.5. Summary of the proposed mitigation strategies at local level.

MS	Cost of MS ($)	Manageability of MSs on registered risks																		
		R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}	R_{17}	R_{18}	R_{19}
3D imagining	40,000						64.1%	74.7%	82.7%	76%							57.6%	80.5%	75.4%	79.5%
3D jigs	75,000						70.1%	85.6%	79.5%											67.4%
Prototyping	155,000	45%	60%	85%	50%				30%				40%						65%	53%
Cast connection	25,600				35%			40%	20%											

Generally, reducing the probability of the occurrence of risks will reduce their exposure at both local and global levels (Equation 4-1 & 4-3). From a global management perspective, the cost limit on the proposed global MSs is defined as the value of the pre-mitigated targeted links that connect targeted risks with other risks, based on stochastic risk assessment results. The results of link quantification (Figure 4.15) are helpful for identifying high-impact links that should be the first target for mitigation. Targeted Risks R_{17} and R_{19} both have links associated with medium-impact consequences connected with the most common risk in modularized projects (R_8) (Figure 4.16.a). Ensuring that the quality control (QC) system achieves the required tolerance level and confirming that fabrication and assembly equipment meets quality criteria during early project phases can reduce the probability of the escalation of links $R_{17} \rightarrow R_8$ and $R_{19} \rightarrow R_8$, respectively. On the other hand, Risk R_4 has two links: a medium-impact one ($R_4 \rightarrow R_{11}$) and one ($R_4 \rightarrow R_{13}$) with a very high impact that might lead to human and structural safety issues, which can be managed via the performance of continuous nondestructive welding tests during the fabrication and assembly processes. The same risk also has another link ($R_4 \rightarrow R_8$) associated with a medium impact that might result in geometric variability issues in the assembled modules, which can be confined by changing welding sequence so that the heat effect is effectively controlled (Figure 4.16.b). Risk R_7 has a link ($R_7 \rightarrow R_8$) with a medium impact that can be decreased through the use of strict quality procedures for checking the dimensional and geometrical conformity of outsourced frames.

Finally, Risk R_8 has two low-impact links: $R_8 \rightarrow R_3$, which can be managed by means of more efficient communication among main project parties throughout all project phases, and $R_8 \rightarrow R_{16}$, which could be addressed through the performance of additional QC checks using highly precise tools. Table 4.6 summarizes the proposed mitigation actions for managing the propagation behaviour of the targeted risks and lists their initial rationally assumed cost and effectiveness values. It should be noted that the value of the pre-mitigated targeted links (i.e., cost limit on global MSs) is $252,920 (Table 4.6).

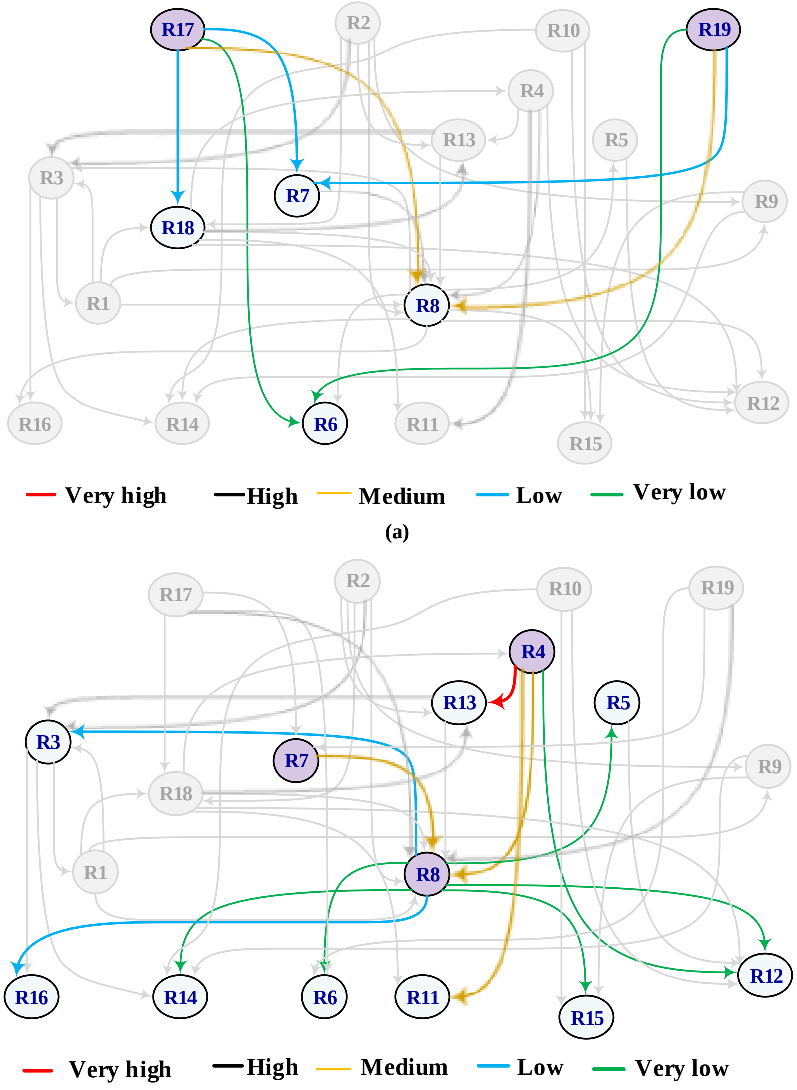


Figure 4.16. Global risk management based on link classification for: (a) source and (b) transitive targeted risks.

Table 4.6. Summary of mitigation actions at global level.

Targeted risk	Targeted link	Link value	Mitigation action	MS cost	Manageability
R_{17}	$R_{17} \rightarrow R_8$	$36,212	Assuring that QC system achieves the required tolerance level	$6,200	70%
R_{19}	$R_{19} \rightarrow R_8$	$35,211	Confirming that fabrication and assembly equipments meet quality criteria	$5,625	85%
R_4	$R_4 \rightarrow R_{11}$	$28,650	Performing continuous nondestructive welding tests during fabrication and assembly processes	$6,300	90%
	$R_4 \rightarrow R_{13}$	$94,550			
	$R_4 \rightarrow R_8$	$25,157	Changing welding sequence to control the heat impact	$5,275	55%
R_7	$R_7 \rightarrow R_8$	$26,266	Employing strict QC procedures to check the dimensional and geometrical conformity of outsourced frames	$4,000	67%
R_8	$R_8 \rightarrow R_3$	$10,437	Efficient communication between main project parties	$13,250	65%
	$R_8 \rightarrow R_{16}$	$20,077	Performing more QC checks using precise tools	$10,440	70%

Figure 4.17 shows the post-mitigated aggregated risk impact after the proposed MSs have been applied at the local and global levels. It should be noted that global MS actions are complementary to local MS ones (i.e., a global MS function does not replace a local MS function). The global MS impact, which is aimed at managing the propagation behaviour of a specific targeted risk, is therefore included in the local risk management plan if the local MS affects that specific targeted risk. For example, 3D imaging has a local impact on specific targeted risks such as $R_6, R_7, R_8, R_{16}, R_{17}$, and R_{19}. However, it has no effect on Risk R_4 (Table 4.5). The global MSs related to targeted Risk R_4 (Table 4.6) are thus not included as complementary actions in the 3D imaging MS.

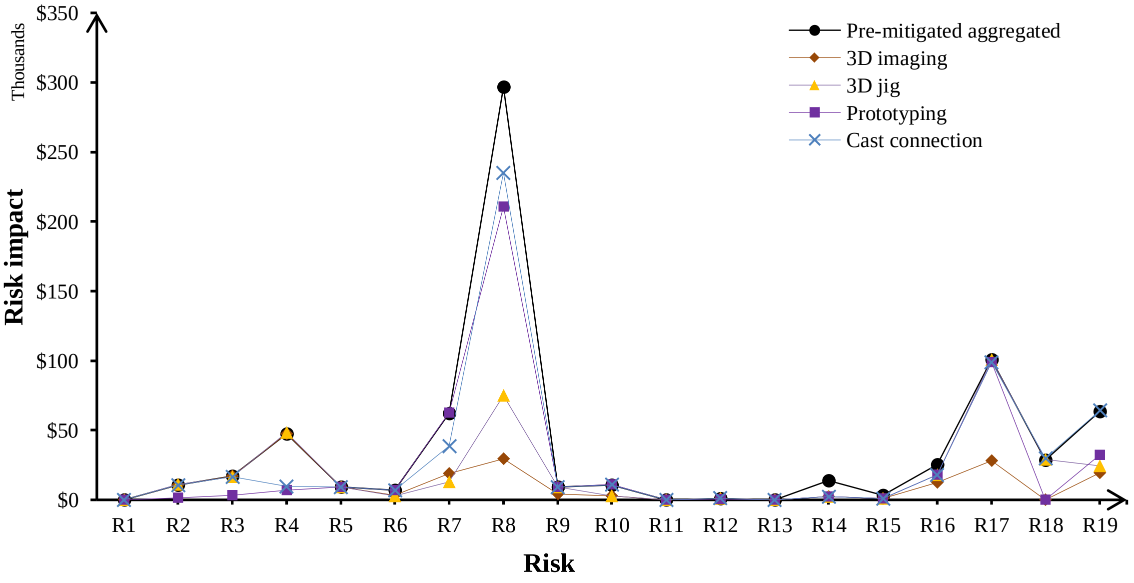


Figure 4.17. The impact of different MSs on the registered risks.

The feasibility of each mitigation scenario has to be re-examined by making sure that the local and global MSs cost and post-mitigated targeted risks are less than the cost limit. The cost limit on the proposed local and global MSs is defined as the summation of the cost of pre-mitigated targeted risks at the local level and the cost of pre-mitigated targeted links at the global level ($133,506+ $252,920= $512,789). Based on the results in Table 4.7, MS_3 and MS_4 will be excluded, as their costs are more than the cost limit.

Table 4.7. Summary of local and global MS cost, cost of pre-mitigated targeted risks, and cost of post-mitigated targeted risks.

MS	**MS cost**			**Cost of pre-mitigated risk (cost limit)**	**Cost of post-mitigated risk**	**Total MS + cost of post-mitig risk < cost limit?**
	Local	**Global**	**Total**			
MS_1: 3D imaging	$40,000	$39,515	$79,515	$512,789	$155,968	Yes
MS_2: 3D jig	$75,000	$33,315	$108,315		$279,129	Yes
MS_3: Prototyping (Mockups)	$155,000	$40,890	$195,890		$429,269	No
MS_4: precisely prefabricated connection	$25,600	$39,265	$64,865		$464,189	No

4.3.5 Risk Response Decision

In the final step, the results of the proposed MSs are represented in a 2D graph to support decision making. Based on the identified cost limit and effectiveness of the MSs at the local and global level, the viable solutions are 3D imaging and 3D jigs. The optimum mitigation action in this case is 3D imaging as it has the least initial cost and highest effectiveness (Figure 4.18 and Table 4.8).

Table 4.8. Summary of cost of MS, pre-mitigated, and post-mitigated targeted risks.

MS	**MS cost**	**Cost of pre-mitig risks**	**Cost of post-mitig risks**	**Efficiency**
3D imaging	$79,515	$512,789	$155,968	69.5%
3D jig	$108,315		$279,129	45.5%
Prototyping (Mockups)	$195,890		$429,269	16.3%
precisely prefabricated connection	$64,865		$464,189	9.5%

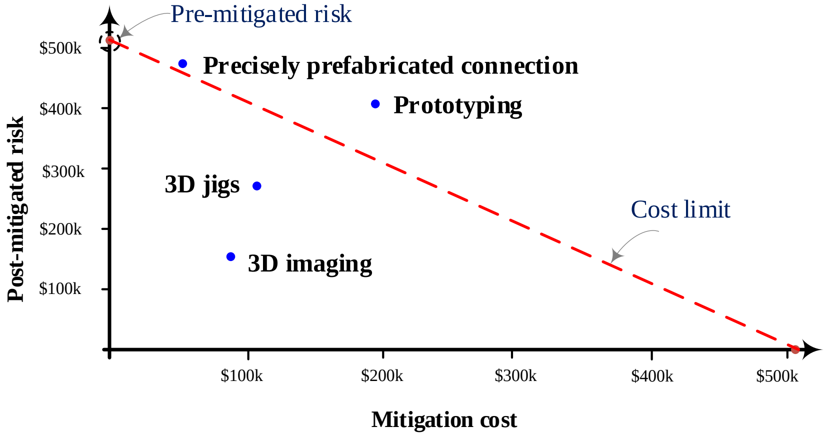


Figure 4.18. 2D graph shows the impact of proposed mitigation strategies on targeted risks value.

4.4 Conclusions

This chapter has presented a systematic framework for the holistic assessment and efficient management of tolerance-related risks in modular construction projects. Existing methods, such as a DSM and AHP pairwise comparisons, are used for identifying and quantifying interactions among tolerance-related risks from a global perspective in conjunction with a classical technique (a P-I risk model) for evaluating risk exposure from a local perspective. A variety of techniques are employed for prioritizing risks locally and globally, such as sensitivity analysis based on Monte Carlo simulation results, risk classification derived from information in a binary DSM, and link quantification established from information in a numerical DSM. Risks with high-level rank and exposure are then targeted and mitigated locally through the management of their probability of occurrence, and globally through the curtailment of their probability of escalation in the event that they do materialize. Finally, different decision criteria, such as the effectiveness and initial cost of proposed MSs, are used as a practical guide for the selection of the optimal solution.

The developed framework was demonstrated using a modular construction case study. From a risk assessment perspective, the results illustrate that project risk managers can enhance their understanding of potential risks impact on the overall project objectives by incorporating a global risk assessment technique into the local and classical methods. From a risk management perspective, integrating local and global risk assessment results can constitute a powerful opportunity, leading to the proposal of more efficient, robust, and proactive mitigation strategies for reducing main risk characteristics, all of which can improve modularization performance and maximize its benefits.

The primary contribution of this research is the development of an efficient risk management framework for the thorough quantitative evaluation of tolerance-related risks and their unique relationships, the proactive management of risk impact at both local and global levels, and the efficient optimization of the trade-offs between early investments and rework costs, all of which aims to support industry practitioners in enhancing their modularization decisions. Other contributions include the introduction of a link quantification and color-coded risk structure network based on the impact of cost and schedule risks for effective risk management, and the integration of local and global risk assessment results into the process of defining a mitigation strategy cost limit. It is expected that the primary users and main beneficiaries of the proposed framework will be modular construction practitioners (e.g., owners, designers, fabricators, and contractors) during the early project phases (i.e., through to the early detailed design).

Although the applicability of the proposed framework has been demonstrated, some limitations can also be identified. From a global risk assessment perspective, adding new risks to update the risk register table following the calculation of the numerical DSM necessitates a repetition of the global risk assessment process, which is time-consuming in practice. For this reason, thorough identification of tolerance-related risks is critical prior to the performance of the AHP pairwise comparisons. In addition, confidence in the determination of an optimal MS is heavily reliant on both the accuracy of the input data (probability of occurrence, probability of escalation, and impact values) and the accuracy of the MS effectiveness value (manageability percentage). The accuracy of the input data can be improved by conducting several workshops between project risk managers and key project parties during the early project phases (mainly during design and engineering) to have a better understanding of the main risk characteristics based on deep analyses of the tolerance-related issues using the opinion of subject matter experts (SMEs), lessons learned documents, and distribution fitting techniques for historical data of previous similar projects.

Recommended directions for the continuation of this research include a rigorous analysis of all potential risks that might affect modularized projects rather than a focus on only tolerance-related risks, a shift that will enable the real complex interactions at different levels to be represented and evaluated. Such an investigation would support the proposal of more efficient solutions for improving overall modularization performance and for maximizing its benefits. In addition, dynamic risk assessment and management techniques using Bayesian theory can be applied to continuously evaluate the performance of MSs, update risk profile, and revise risk response plans, all of which support industry practitioners to make better modularization decision.

Chapter 5

Dynamic Risk Management Methodology for Tolerance-Related Risks using Bayesian Theory

5.1 Introduction

This chapter presents a systematic methodology that employs Bayesian inference theory for the dynamic assessment and proactive management of excessive geometric variability issues. The methodology developed includes a practical process for continual: 1) updating of initial estimates of the performance of tolerance-based mitigation strategies based on real-time data, 2) reassessment of the risk profile, and 3) refinement of risk response decisions. The results of the case study described subsequently in this chapter demonstrate that key project stakeholders and modular construction managers (e.g., designers, fabricators, and contractors) can efficiently reduce uncertainty in tolerance-related risk estimates and proactively manage impacts, to improve modularization performance and maximize its benefits.

5.2 Proposed Methodology

This section summarizes the proposed methodology (Figure 5.1) for dynamic assessment and proactive management of tolerance-related risks in modular construction projects. The developed methodology is composed of two major steps: 1) static risk assessment and management, which will be performed based on the information available at early project phases (e.g., front-end planning, design and engineering), and 2) dynamic risk assessment and management, which will be performed based on real-time data extracted from the fabrication, transportation, and erection phases of the project. The application of the proposed methodology facilitates re-evaluating the mitigation strategy (MS) effectiveness, re-assessing the risk profile, and revising the risk response decisions to improve the overall modularization performance in construction projects. The next sub-sections explain the details of each step.

5.2.1 Static Risk Assessment and Management

The first step is similar to the classical and standard project risk assessment and management approach (ISO, 2009; PMI, 2013), which aims to identify, analyze, evaluate, and manage tolerance-related risks in modular construction projects. ***Risk identification*** aims to identify potential tolerance-related risks that might have negative effects on the overall modularization performance (ISO, 2009; PMI, 2013). The risk identification process can be carried out using several techniques such as analogy (e.g., checklist), heuristic (e.g., open-ended questions, interviews), and analytic (e.g., scenario analysis) (ISO, 2009; Muriana et al., 2017; Yoe, 2011) approaches. ***Risk analysis***, which is the second step, aims to analyze the main characteristics (probability of occurrence and impact) of identified risks, using subjective and/or objective data. In the ***risk evaluation*** step, a probability-impact (P-I) risk model can then be employed to quantitatively evaluate risks using either a deterministic (single-point estimate of potential impact) or a probabilistic approach (probability distribution function of potential impact) (Acebes et al., 2015; Vose, 2008; Yoe, 2011). In the last step, ***risk management***, risks with high impact will be targeted for mitigation purposes (i.e., reducing probability of occurrence and/or impact). Different decision criteria (e.g., effectiveness, confidence level, sustainability and maintainability, risk tolerance, risk attitude, etc.) can be used to identify the optimum mitigation scenario. The results of static risk assessment and management will include a list of expected tolerance-related risk exposures (pre-mitigated and post-mitigated risks) and associated mitigation strategies (cost and effectiveness of each MS).

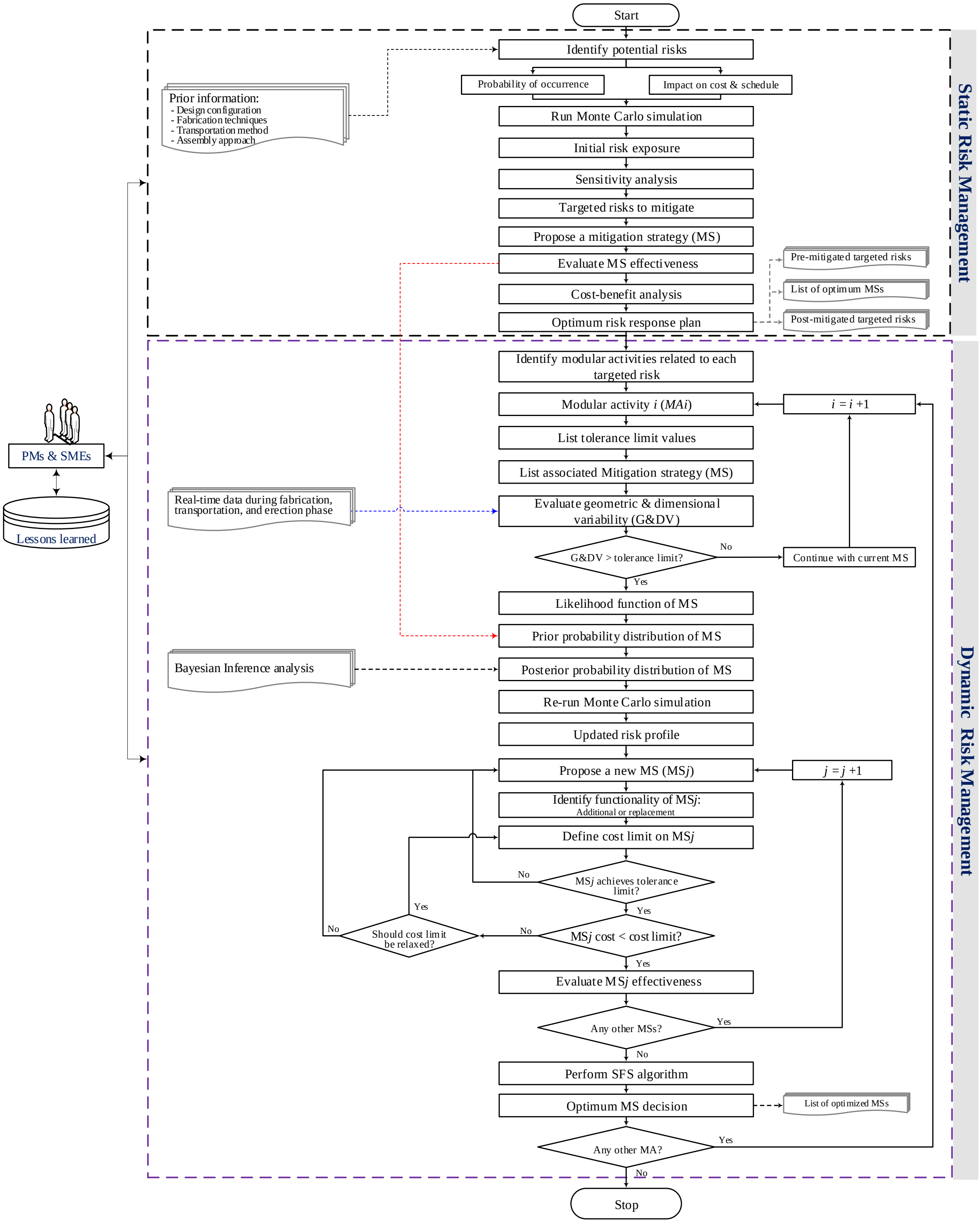


Figure 5.1. The proposed methodology for dynamic management of tolerance-related risks in modular construction projects.

5.2.2 Dynamic Risk Assessment and Management

The second step, which is the focus of this chapter, aims to achieve continual monitoring and control of proposed risk management plans that result from the first step. The continual assessment and dynamic management of tolerance-based mitigation strategies follows four main steps:

Step 1: ***Identify relevant modular activities***. Modular activities are defined as the required tasks to fabricate, assemble, and complete a volumetric unit (module). The relevant modular activities affected by targeted risks will be identified by project risk managers for continual monitoring purposes. For each modular activity, the identified tolerance limits, which are defined either by construction tolerance codes (AISC, 2016; BSI, 2011) or by the modular design team, and associated mitigation strategies (MSs) will be compiled in a table (Table 5.1) so that the overall performance of the MSs employed can be monitored and controlled. It should be noted that the list of targeted risks must be flexible so that new risks that have been underestimated based on the static risk assessment and management step can be added during the dynamic risk management step.

Table 5.1. Example of the created link between relevant modular activities and targeted risks, tolerances, and employed MSs.

Modular activity	Targeted risk	Targeted risk	Tolerance (acceptable G&DV)	Employed mitigation strategy
MA_1	R_1 & R_4	R_1 & R_4	$10\ mm$	MS_1 & MS_2

Step 2: ***Evaluate mitigation strategy (MS) effectiveness***. The geometric and dimensional variabilities (G&DV) of relevant modular activities will be assessed using real-time data extracted from the fabrication, transportation, and erection processes. Deviation analysis results will then be used for verifying whether the performance of the currently employed MSs is meeting the required tolerance limits. The performance of inefficient MSs will be re-evaluated using Bayesian inference theory, which includes analyzing three main parameters: 1) prior function, 2) likelihood function, and 3) posterior function.

The ***prior function*** represents the initial assessment of performance of each MS, which is usually evaluated as a discrete value (e.g., manageability percentage) during the early project phases (i.e., at the static risk assessment and management step). A *Beta* distribution is generally used to represent the prior function, as it can describe the uncertainty about the occurrence of an event using the two main distribution parameters (α_{prior}, which represent the number of successes and β_{prior}, which represent the number of failures) (Kalantarnia et al., 2010; Meel et al., 2006; Vose, 2008). The main parameters of the *Beta* distribution can then be estimated such that the mean value of the *Beta* distribution would match the discrete value of the MS performance (Equation 5-1) (Vose, 2008).

$$\mu = \frac{\alpha_{prior}}{\alpha_{prior} + \beta_{prior}} = MS\ performance \qquad 5\text{-}1$$

The ***likelihood function*** represents a discrete function generated based on real-time data collected on the performance of the currently employed MSs during the fabrication, transportation, and erection phases of the project. This function is defined by a set of failures and successes to achieve required the tolerance level. Many approaches exist to select the distribution of the likelihood function. However, among the most convenient is to use the conjugate pair of the prior function (e.g., *Beta-Binomial*, *Poisson-Gamma*, etc.) (Vose, 2008). Thus, a *Binomial* distribution will be used to represent the likelihood function, as it is the conjugate pair of the prior function (*Beta* distribution). This selection is convenient since real-time data are specific numbers within a discrete domain, which are also best represented by a *Binomial* distribution. The likelihood function can be defined as:

$$P(Data/x) = \binom{n}{s} x^{s}(1-x)^{f} \qquad 5\text{-}2$$

Where $P(Data/x)$ is the likelihood function, x is performance of current employed MS, n is the total number of trials, s is number of successes, and f is number of failures.

The ***posterior function***, which is also called the improved/revised probability distribution, represents the performance of the currently employed MSs based on real-time data and up-to-date analysis. The posterior function is calculated based on the prior distribution and likelihood function using Bayesian inference. Bayesian inference is a technique that helps risk analysts to update the probability for a hypothesis as more evidence or information becomes available based on Bayes' theorem (i.e., Bayesian inference describes a learning process) (Meel, 2007; Robert, 2007). Since the prior and likelihood distributions are conjugate (*Beta-Binomial*), the distribution of the posterior function will be the same as the prior distribution (i.e., *Beta* distribution with $\alpha_{posterior} = \alpha_{prior} + s$ and $\beta_{posterior} = \beta_{prior} + f$) which can be described as follow:

$$P(x/Data) = \frac{P(x) \times P(Data/x)}{P(Data)} \qquad 5\text{-}3$$

Where $P(x/Data)$ is the posterior function, $P(x)$ is the prior function, $P(Data/x)$ is the likelihood function, and $P(Data)$ is the probability of data observed.

Step 3: Update the risk profile. Based on the results of the previous step, the Monte Carlo simulation is repeated to evaluate the updated risk exposure, taking into account the revised performance values of the currently employed MSs. The updated risk impacts will then be used for defining the cost limits on MSs that will be proposed for increasing the performance of the current, inefficient MSs.

Step 4: Scenario analysis. Different MSs are proposed for managing excessive geometric variability issues in modular components and assemblies. The MSs proposed should comply with two conditions: 1) they must achieve the specified tolerance limits, and 2) they must cost less than the cost limit. The cost limit will be defined based on the functionality of the proposed MS: whether it is a replacement for or an addition to the current, inefficient MS. In the case in which the proposed MS is replacing the current, inefficient MS, the cost limit will be identified as the cost of the pre-mitigated value of the risk(s) affected by the current, inefficient MS, which is defined based on the static risk assessment step (Equation 5-4).

$$\begin{aligned}&Cost\ limit\ on\ replacement\ MS\\ &\leq cost\ of\ pre\ mitigated\ value\ of\ risk(s)\ effected\ by\ current\ inefficient\ MS\end{aligned} \qquad 5\text{-}4$$

If the proposed MS will be employed along with the current MS (i.e., additional MS), the cost limit will be defined as the difference between the cost of pre-mitigated risk(s) affected by current inefficient MS and a summation of the current inefficient MS cost (which is already been spent) and the cost of updated post mitigated value of risks affected by current inefficient MS (Equation 5-5).

$$\begin{aligned} &Cost\ limit\ on\ additional\ MS \\ &\quad \leq cost\ of\ pre\ mitigated\ risk(s) - [cost\ of\ current\ inefficient\ MS \\ &\quad + cost\ of\ updated\ post\ mitigated\ risk(s)] \end{aligned} \tag{5-5}$$

After identifying the candidate MSs, the effectiveness (manageability percentage) of these MSs will be evaluated based on objective data (e.g., technical specifications of MSs) and/or subjective data (e.g., opinions and insights from subject matter experts).

Step 5: Optimize risk response decisions. Based on the results of the previous step, for each candidate MS, modularization decision makers can easily/trivially decide whether to employ it or not. However, if there is a list of n potential MSs, there will be $2^n - 1$ combinations of MSs and deciding which combination is the optimum could be a time-consuming and impractical process. Heuristic algorithms can thus be an efficient technique to find the optimum combination of MSs that has the biggest impact on lowering the risk profile. Towards this end, a greedy algorithm can be developed using the Sequential Forward Selection (SFS) technique to find the optimum combination of MSs (Algorithm 1). In each iteration/step, the MS with the highest performance (i.e., highest risk reduction percentage) is selected until the cost limit on the MS is exhausted, a list of potential MSs are tested, or the risk profile is reduced below a defined threshold (i.e., the expected risk exposure is effectively zero).

The developed methodology described in this section is generic and can be applied to range of modular construction projects.

Algorithm 1. Optimum selection of mitigation strategy using SFS technique.

```
The objective function (OF): is to reduce overall risk impact → $R_i = \sum_{i=1}^{n} P_i \times I_i$.
The constraint: is cost limit on proposed mitigation strategy (MS).
Variables: are the proposed MSs.
  $CL$   =  cost limit on MSs;
  $L$    =  list of potential MSs ($MS_1, MS_2, \cdots, MS_n$);
  $R_a$  =  affected risk(s) by potential MSs ($a = 1,2,\cdots,n$);
  $E$    =  efficiency of MS;
  $A$    =  combination of MSs → $A = \emptyset$

While $L \neq \emptyset$, Do
Begin
        For each $MS_i \in L$
        Select $MS^*_i = \arg max\ E(MS_i)$
        Identify affected risk(s) by $MS^*_i = R_a$
                IF $C(MS^*_i) < CL$,  &  $C(MS^*_i) < C(R_a)$
                        Evaluate the impact of $MS^*_i$ on $R_a$
                        Estimate the cost of post-mitigated affected risk(s): $PR_a$
                        Ensure $[C(MS^*_i) + C(PR_a)] < CL$, & $[C(MS^*_i) + C(PR_a)] < C(R_a)$
                Else remove $MS^*_i$ from list: $L = L \setminus MS^*_i$
                End
        End
        Add $MS^*_i$ to $A$: ($A = MS^*_i \cup A$)
        Remove $MS^*_i$ from L: ($L = L \setminus MS^*_i$)
        Update $CL$: $CL = CL - C(A)$
        Update $R_a$: $R_a = PR_a$
End
Report A as the optimum combination of MSs
```

5.3 Case Study

The case study investigated in this research chapter related to a one-storey modular data centre project comprised of 16 modules, which were completely built and assembled offsite at a fabrication shop and then transported to project site for final alignment (Figure 5.2). This case project was built using the traditional project delivery method (design-bid-build) where there was lack of shared information about modularization process capabilities for fabrication, transportation, and erection, during the early design phases. Thus, numerous out-of-tolerance and out-of-alignment issues were experienced during the fabrication and erection project phases (Figure 5.3). Information concerning the case study was obtained from the industry partner. In addition, several site visits were conducted to the shop during the fabrication and assembly processes, and to the project site during the module fit-up and alignment. The purpose of the case study is to demonstrate the effectiveness of the proposed methodology (Figure

5.1), recognizing that it is generic and can be applied to a range of modular construction projects.

(a) (b) (c) (d) (e) (f)

Figure 5.2. The case study during: (a) fabrication and assembly processes, (b) temporary storage area, (c) site preparation and building concrete foundation, (d) modules installation at project site, (e) connection of MEP systems, and (f) completed building.

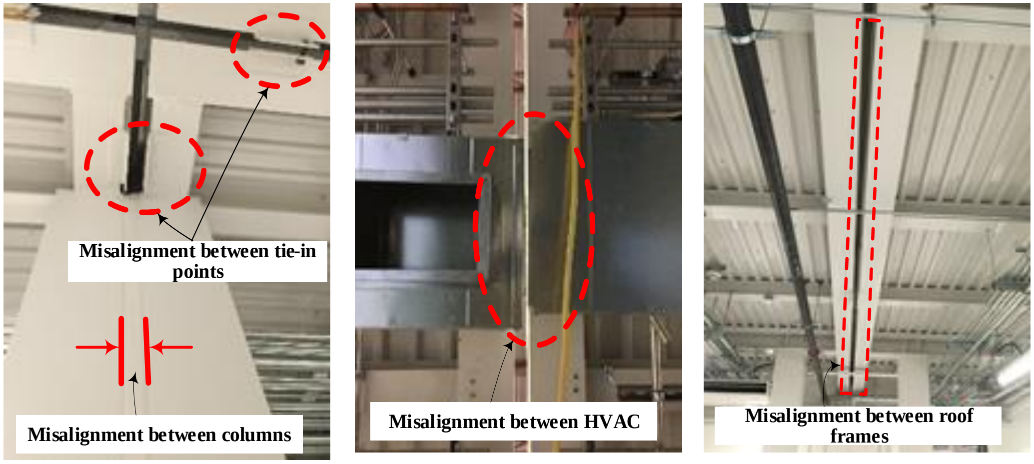


Figure 5.3. Misalignment issues between modules and their components during erection phase at project site.

5.3.1 Static Risk Assessment and Management

The main tolerance-related risks that might affect the overall module geometry were identified and refined based on face-to-face meetings and discussions with industry partner of this research (fabrication team), meetings with the site-installation and erection company, and literature review (Table 5.2). The selection criteria considered for identifying tolerance-related risks were: 1) direct and significant impact of risk events on the overall dimensional and geometric tolerances, and 2) ability to capture real-time data concerning risk events during the fabrication, transportation, and erection phases of the project. It should be noted that the number and scope of the integrated risks in this chapter is reduced compared to the identified risks in Chapter 3 and Chapter 4, because there was only sufficient real-time data and accurate information about the characteristics of these risks to employ the developed dynamic risk management methodology.

Table 5.2. Tolerance-related risks that might affect module geometry.

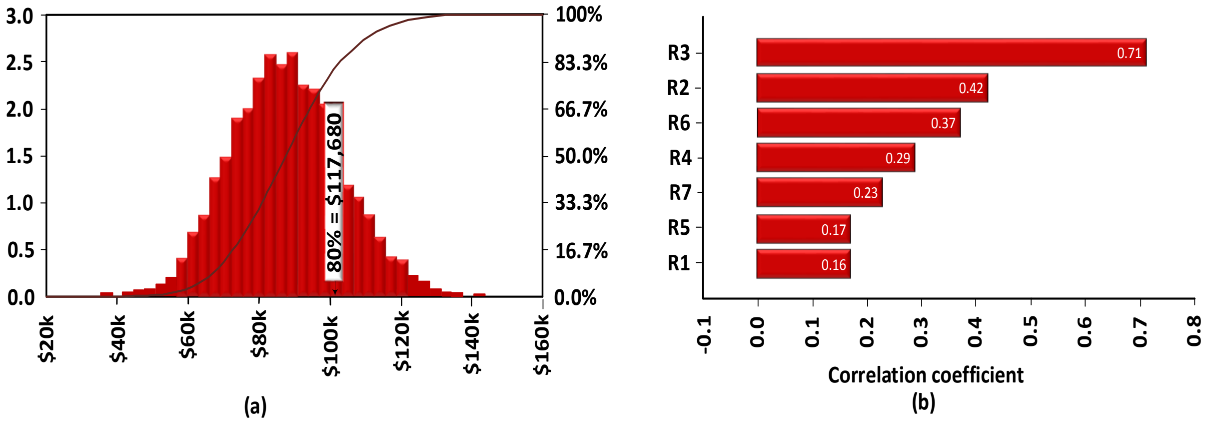
Risk ID	**Risk name**	**Category of impact**	
		Schedule	**Cost**
$\boldsymbol{R_1}$	Sub-assemblies (parts) have excessive geometric & dimensional variation	Delay	Extra cost
$\boldsymbol{R_2}$	Non-volumetric units (frames) have excessive geometric & dimensional variation	Delay	Extra cost
$\boldsymbol{R_3}$	Volumetric unit (module) has excessive geometric & dimensional variation	Delay	Extra cost
$\boldsymbol{R_4}$	Welding defects	Delay	Extra cost
$\boldsymbol{R_5}$	Fabrication errors	Delay	Extra cost
$\boldsymbol{R_6}$	Inefficient use of fabrication and assembly equipments	Delay	Extra cost
$\boldsymbol{R_7}$	Inefficient lifting and hauling equipments	Delay	Extra cost

The identified tolerance-related risks were then quantitatively analyzed through estimating probability of occurrence and impact. The analysis was performed based on the available information for the current case study (e.g., CPM schedule, fabrication and assembly cost codes, and change request extra reports), previous lessons learned documents provided by the industry partner, rational assumptions based on meetings and discussions with fabrication and erection teams of the current case study project (e.g., modular design manager, project manager, plant manager, risk management director, and site superintendent). Table 5.3 summarizes the values assigned to the probability of occurrence and the potential impact range with respect to cost and schedule for each risk. Due to lack of shared and available information needed to generate optimistic and pessimistic values for impacts, rational assumptions were made to develop these values, for the purpose of demonstrating the application of the proposed methodology. The optimistic and pessimistic values of risk impact on cost and schedule can be evaluated by conducting several workshops between the project risk managers and key project parties during the early project phases (mainly during design and engineering) to define the minimum and maximum impact values of risks if they materialize based on deep analyses of the tolerance-related issues using the opinion of subject matter experts (SMEs), lessons learned documents, and distribution fitting techniques for historical data of previous similar projects. It should be noted that the risk impacts on cost and schedule were estimated on a per volumetric module basis.

Table 5.3. The estimated probability of occurrence and impact ranges for tolerance-related risks.

Risk	Probability (%)	Impact					
		Schedule (days)			Cost ($)		
		Min	Most likely	Max	Min	Most likely	Max
$\boldsymbol{R_1}$	17.67	0.35	0.37	0.60	600	650	1,050
$\boldsymbol{R_2}$	37.70	0.80	0.85	1.45	910	1,100	1,600
$\boldsymbol{R_3}$	40.59	1.15	1.20	1.95	2,050	2,170	3,500
$\boldsymbol{R_4}$	18.75	0.60	0.75	1.05	910	1,140	1,700
$\boldsymbol{R_5}$	3.66	0.85	1.20	1.95	510	650	1,200
$\boldsymbol{R_6}$	18.28	0.75	1.15	1.80	850	1,050	1,700
$\boldsymbol{R_7}$	25.10	0.25	0.37	0.90	700	900	1,100

After estimating the main risk characteristics (probability of occurrence and impact ranges), a probabilistic risk assessment (Monte Carlo simulation) was conducted for risk modelling purposes. The *@Risk*® software from *Palisade* is used as a platform to perform the Monte Carlo analysis. Triangular distributions were used to represent the impact ranges, due to lack of available data to perform distribution fitting techniques (i.e., goodness-of-fit tests). The results of the Monte Carlo analysis after 10,000 iterations at 80% confidence level (i.e., 80th percentile) revealed that the total expected cost of risks on the project is $117,680 (Figure 5.4.a). Also, the results of a sensitivity analysis showed that risks R_3, R_2, and R_6 have the highest impact on driving the overall project cost and schedule (Figure 5.4.b).



(a)

(b)

Figure 5.4. The results of Monte Carlo analysis: (a) PDF & CDF of expected risks exposure, and (b) sensitivity analysis using tornado graph of correlation coefficients.

The tolerance-related risks with high impact were then targeted for mitigation purposes using different scenarios (Table 5.4 and Figure 5.5). The effectiveness of currently employed MSs (Table 5.4) was evaluated based on technical specifications and rational assumptions derived from several discussions with the fabrication and production team (plant manager, project superintendent, and project lead foreman). The MS cost was evaluated as either part of the overhead cost as these MSs are incurred in the fabrication shop (e.g., MS_1, MS_2, and MS_6) or as a direct investment cost (e.g., MS_3, MS_4, and MS_5) (Table 5.4). For instance, the cost of MS_2 (2D jig), which was estimated as an overhead cost, includes maintenance and training costs. Based on the industry best practices recommendation (CII, 2006), the average annual maintenance cost was assumed to be 5% of the initial MS cost. Thus, the annual maintenance cost of a 2D jig was estimated as $0.05 \times \$750k = \$37.5k$. As a rough estimate, the monthly maintenance cost was considered one-twelfth of the annual maintenance allocation (i.e., $= \$37.5k/12 = \$3.125k$). Since the offsite fabrication and assembly works of the current case study project took 3 months to complete, the total maintenance cost of the 2D jig is evaluated as $\$3.125k \times 3 = \$9{,}375$. The training cost was evaluated as a percentage of the total labour cost required to build the main structure of a volumetric module using 2D jig (i.e., $0.1 \times \$11{,}250 = \$1{,}125$). The total cost of MS_2 is thus estimated as \$10,500 ($\$9{,}375 + \$1{,}125$) (Table 5.4).

Table 5.4. The applied MSs to manage tolerance-related risks.

Applied mitigation strategy (MS)	Effectiveness	MS cost ($)	Affected risks
MS_1: Laser meter, measuring tape, caliper, and level	90%	100	R_1, R_2
MS_2: 2D jig (controlling table)	95%	10,500	R_3
MS_3: Visual inspection for welds execution by certified welding inspector	85%	3,500	R_4
MS_4: QC plans for continuous supervision of fabrication and assembly activities	90%	2,500	R_5
MS_5: Quality assurance strategy to prevent any deficiencies in use of fabrication and assembly equipments	95%	3,700	R_6
MS_6: Application of rectangular lifting frame	85%	500	R_7

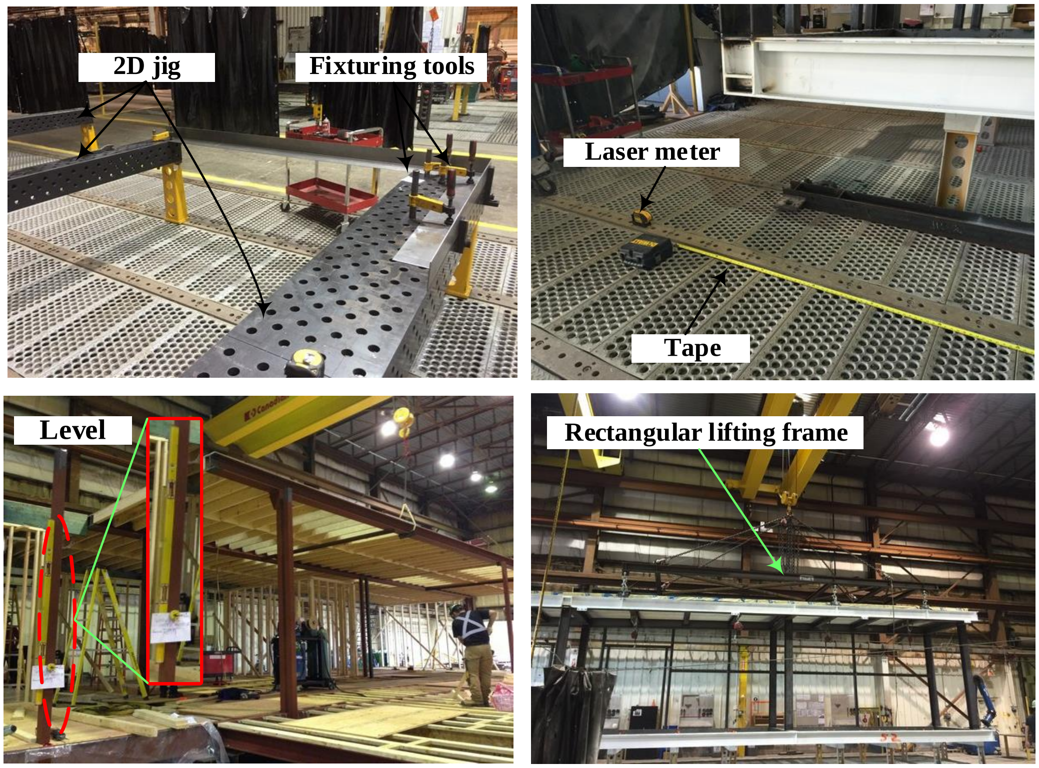


Figure 5.5. Examples for some of the current MSs at the fabrication shop.

Figure 5.6 shows the expected post-mitigated tolerance-related risk impact after applying the proposed mitigation strategies. It should be noted that the feasibility of the current MSs is verified by making sure that the MS cost and post-mitigated risk is less than the cost limit, which is assumed in this research as the value of pre-mitigated targeted risks ($117,680 as shown Figure 5.4.a). The project risk managers will use the results shown in Figure 5.6 as a base to update the post-mitigated risk profile based on the performance of proposed mitigation strategies during the fabrication, transportation, and erection phases of the project.

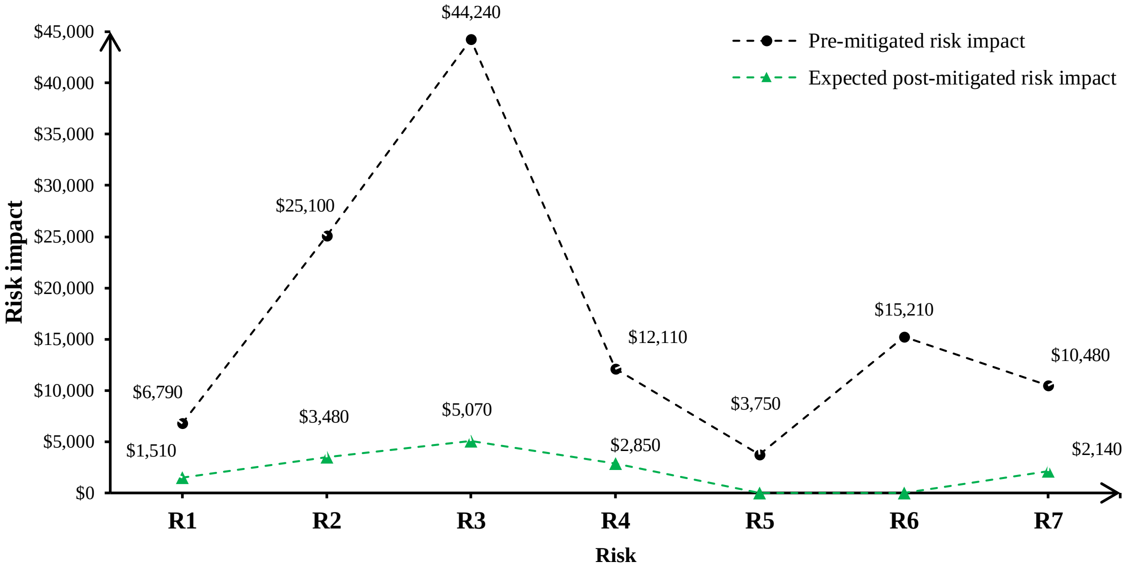


Figure 5.6. The impact of current MSs on tolerance-related risks.

5.3.2 Dynamic-Based Risk Assessment and Management

In this step, the performance of the currently employed MSs (Table 5.4) will be monitored on a dynamic and continual basis, using real-time data extracted, mainly, from fabrication and assembly processes of the current case study project. The ***first step*** of dynamic risk management starts with linking the tolerance-related risks, acceptable geometric variabilities (tolerances), and proposed mitigation strategies (MSs) to the relevant modular activities, all of which increase perceptions and awareness of expected risks that need to be avoided/managed. It should be noted that the current research focuses on performing the continual monitoring for the modular activities that will form the main structure of volumetric modules (Figure 5.7), as they have a high impact on the dimensional fit-up and geometry of other modular systems (e.g., mechanical, electrical, plumbing, service, etc.) and on the overall geometry of aggregated structure at the project site. Table 5.5 summarizes the modular activities that will be targeted for monitoring purposes, along with the expected risks, and currently employed MSs to manage excessive geometric variabilities. Figure 5.8 shows the tolerance limits (acceptable geometric variabilities), which are derived from tolerance standards (BSI, 2011), for targeted modular activities.

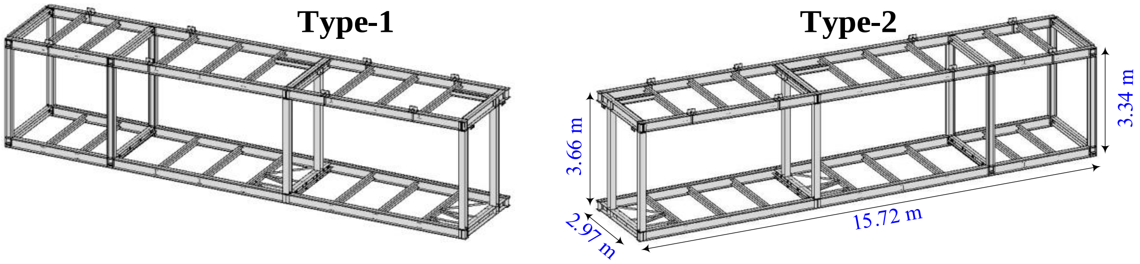


Figure 5.7. The main structure of modules in the current case study project.

Table 5.5. Summary of modular activities need to be monitored at fabrication phase, along with potential risks, and employed MSs.

Modular activity	Expected risks	Employed MS
MA_1: Columns arrival from suppliers and offload at fabrication shop	R_1	MS_1 & MS_2
MA_2: Frames arrival from suppliers and offload at fabrication shop	R_2 & R_5	MS_1, MS_2 & MS_5
MA_3: Install and weld clip angles (tie-in points) to roof frame	R_1 & R_5	MS_1
MA_4: Tack and weld the columns to base (floor) frame	R_1, R_2, & R_4	MS_1, MS_2 & MS_3
MA_5: Tack and weld roof frame to the columns	R_3, R_4, R_6, & R_7	MS_1, MS_2, MS_3, MS_5 & MS_6
MA_6: Transfer the completed unit (volumetric module) to floor	R_7	MS_6

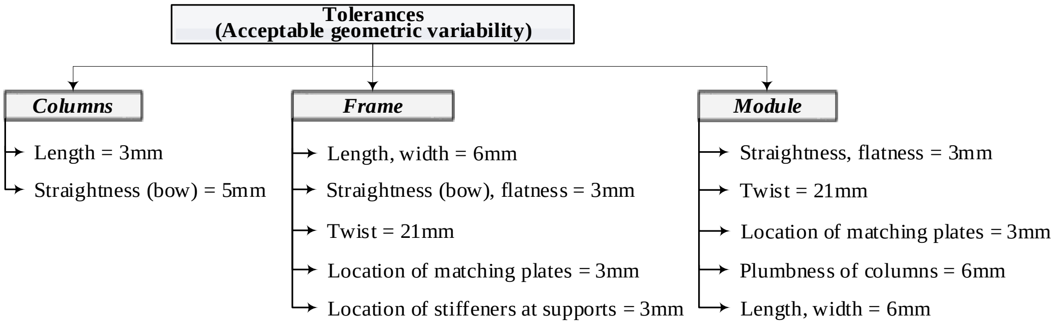
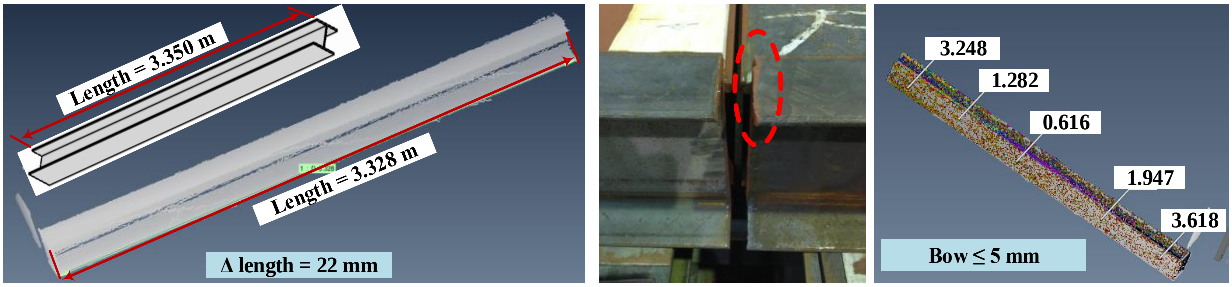


Figure 5.8. Acceptable geometric variabilities (tolerances) for different modular components of current case study.

In the ***second step***, the performance of the currently employed mitigation strategies (MSs) will be evaluated through assessing the compliance between dimensional and geometric variabilities of modular components and design tolerances and specifications. Real-time information extracted from deviation analysis results using laser scanning technology, quality control reports, and lessons learned documents, has been used to assess dimensional and geometric quality of modular components and assemblies. For instance, the performance of the mitigation strategies $MS_1$and MS_2 is evaluated using laser scanning technology, which captures 3D point clouds/images (geometric data) for modular components during assembly processes at fabrication shop of current case study project (Figure 5.9). PolyWorks®, an industrial 3D metrology software, and Cloud Compare®, a 3D point cloud processing software, were then used to perform deviation analysis by comparing the as-built state, which is obtained through the use of a FARO LS 840HE laser scanner, with the as-designed state, which is extracted from a building information model (BIM). The results revealed that the current modular components and assemblies have experienced some geometric changes, which are, in some cases, exceeding tolerance limits. For example, 4 out of 12 analyzed columns have length issues (Figure 5.10.a), which may have resulted from deficiencies in fabrication machines and equipment (cutting tools) (Figure 5.10.b). However, all these columns are within acceptable bow limits (Figure 5.10.c).

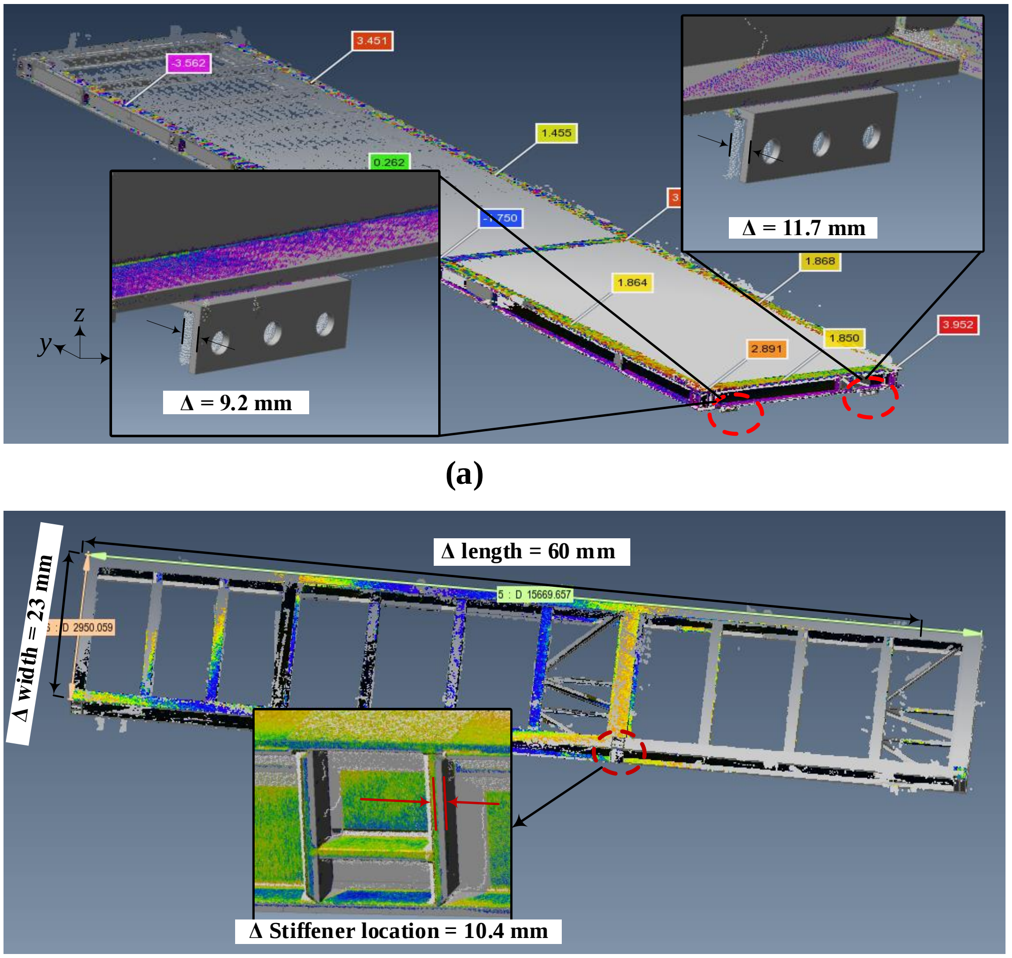
Figure 5.9. Application of laser scanning technology for real-time data collection.



(a) **(b)** **(c)**

Figure 5.10. Deviation analysis output for columns.

On the other hand, out of 5 analyzed frames (roof and floor frames), 3 frames have excessive dimensional variabilities such as errors in location of matching plates, length and width issues of assembled frames, and positional errors in the locations of stiffeners at the supports (Figure 5.11). Finally, the results of analyzing the overall geometry of 8 assembled modules revealed that the main structure of 3 modules have experienced excessive deformation along the roof frame beam, dimensional variability associated with the location of matching plates due to the effects of accumulation of variabilities in the assembled modules (Figure 5.12.a), out-of-plumbness of the installed columns (Figure 5.12.b), and positional errors in the location of roof frame, which are large enough to be detected visually (Figure 5.12.c).



(a)

(b)

Figure 5.11. Results of deviation analysis for frames: (a) roof frame, and (b) floor frame.

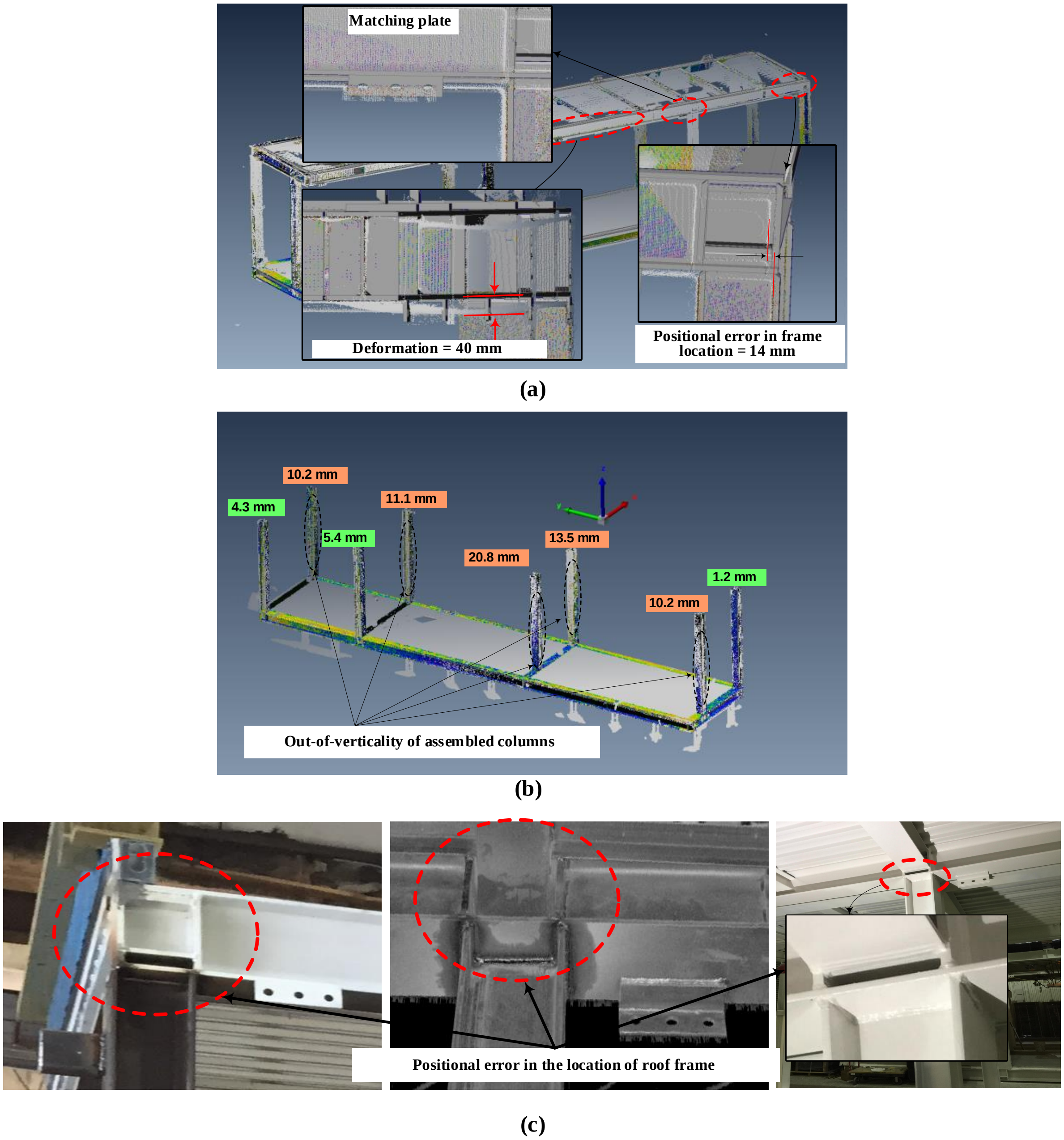


Figure 5.12. Deviation analysis results for the overall assembled modules: (a) overall geometry of a module, (b) plumbness of columns, and (c) location of roof frame.

On the other hand, the performance of MS_3 (visual inspection of welding execution by a certified welding inspector) was evaluated based on the quality control reports provided by the industry partner of case study project. The results revealed that 3 modules out of 16 had welding defects (i.e., the welds were did not achieve full penetration). The effectiveness of MS_4 in managing Risk R_5 (fabrication errors) was assessed based on the information provided through meetings with the fabrication crew (plant manager and project lead foreman) during assembly processes at the fabrication shop. The modules of the case project were designed to be tiled at the roof frames and thus the column height will be different (Figure 5.7). As a result of incomplete fabrication and production drawings, which has created "design-and-go" situations, several errors were made during columns installation with floor frames, where number of columns had to be de-assembled, installed, and welded in the proper location (Figure 5.13). This issue was experienced in one module.

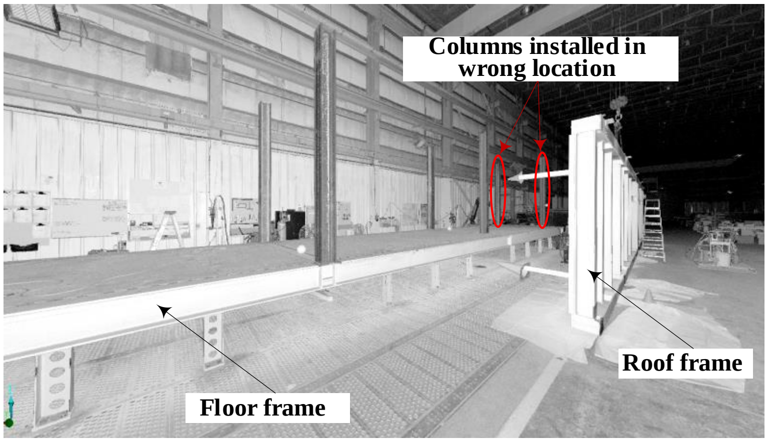
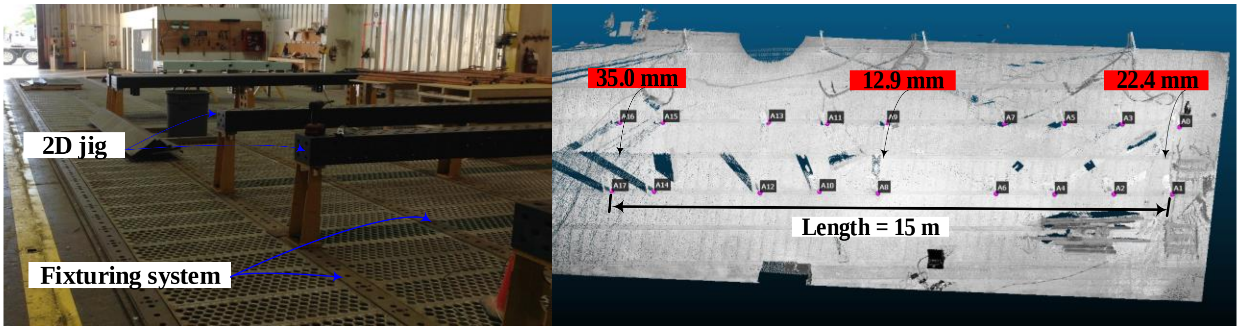


Figure 5.13. Fabrication error during columns' installation to floor frame.

The performance of the mitigation strategy MS_5 is evaluated based on the overall geometry of the 2D jig (framing table used for fit-up and aggregation of the module), which has very tight flatness tolerances (±0.23 mm per 15 m length) (Figure 5.14.a). The results of a plane deviation analysis using laser scanning technology revealed that the fixturing system (on which the 2D jig sits) has more dimensional variability than the accuracy of the table system. The deviation pattern was in the bow shape where the centre is lower than the left edge by 22.1 mm, and lower than right edge by 9.5 mm (Figure 5.14.b). Finally, the effectiveness of mitigation strategy MS_6 (application of rectangular lifting frame) was evaluated based on the ability of the rectangular hauling frame (Figure 5.15.a), which replaced the previous lifting method using inclined cables (Figure 5.15.b), to install the roof frame in the right position without spending any extra cost, time, and resources to achieve positional tolerance. Since the length of current lifting frame was not long as the length of the module, the inclined cables were still in use to lift modular components. Based on quality control reports and discussions with fabrication crew, the placement of 4 roof frames out of 14 analyzed frames took more time and resources to achieve required positional tolerances.



(a) (b)

Figure 5.14. Framing table at fabrication shop: (a) 2D jig and fixturing system, (b) deviation analysis results of the fixturing system.

(a) (b)

Figure 5.15. Placement of roof frame using: (a) rectangular lifting frame and inclined cables, and (b) inclined cables.

After evaluating the performance of the currently employed mitigation strategies using real-time data (i.e., estimating the likelihood function), Bayesian inference was used to update the overall performance values taking into account the parameters of both the prior distributions and likelihood functions. The following example shows how the calculations were made to get the updated performance for mitigation strategy MS_2 (Table 5.6). Based on the prior information available at the static risk assessment and management step, the performance of MS_2 was evaluated as 95% (Table 5.4). It is assumed that all of the mitigation strategies follow *Beta* distributions, which describe the uncertainty in the occurrence of an event using two distribution parameters (α and β) (Kalantarnia et al., 2010; Meel et al., 2006; Vose, 2008). The parameters of the *Beta* distribution for MS_2 (α_{prior}= 19 and β_{prior}= 1) are selected such that the mean value of *Beta* distribution ($\mu = \alpha_{prior} / [\alpha_{prior} + \beta_{prior}]$) would match the performance value of MS_2 (95%) (Vose, 2008). The parameters of the likelihood function (***f***: number of failures, and ***s***: number of successes) are extracted from the deviation analysis results using laser scanning technology which showed that 3 modules out 8 experienced excessive geometric variability issues (i.e., f = 3 and s = 5). The parameters of the posterior distribution, $\alpha_{posterior}$ and $\beta_{posterior}$, are then estimated as 4 and 24 respectively ($\alpha_{posterior}$= 19 + 5 = 24; $\beta_{posterior}$= 1 + 3 = 4). The updated performance of MS_2 is then evaluated as the mean value of the posterior distribution ($\mu = 24 / [24 + 4] = 85.71\%$). Table 5.6 summarizes the updated performance values of all of the currently employed mitigation strategies. The results show that the updated performance values for most of the mitigation strategies are less than the estimated values based on the available information at the early project phases (e.g., planning, engineering and design) (Figure 5.16), which confirms the importance of applying the proposed methodology for dynamic risk management using real-time and up-to-date modularization process capability data.

Table 5.6. Summary for the updated performance (posterior distribution) for each mitigation strategy.

MS	**Initial performance**	**Distribution**	**Prior distribution**		**Likelihood function**		**Posterior distribution**		**Updated performance**
			$\boldsymbol{\alpha_0}$	$\boldsymbol{\beta_0}$	$\boldsymbol{s}$	$\boldsymbol{f}$	$\boldsymbol{\alpha_1}$	$\boldsymbol{\beta_1}$	
MS_1	90%	*Beta*	9	1	10	7	19	8	70.37%
MS_2	95%	*Beta*	19	1	5	3	24	4	85.71%
MS_3	85%	*Beta*	17	3	13	3	30	6	83.33%
MS_4	90%	*Beta*	9	1	15	1	24	2	92.31%
MS_5	95%	*Beta*	19	1	3	4	22	5	81.48%
MS_6	85%	*Beta*	17	3	10	4	27	7	79.41%

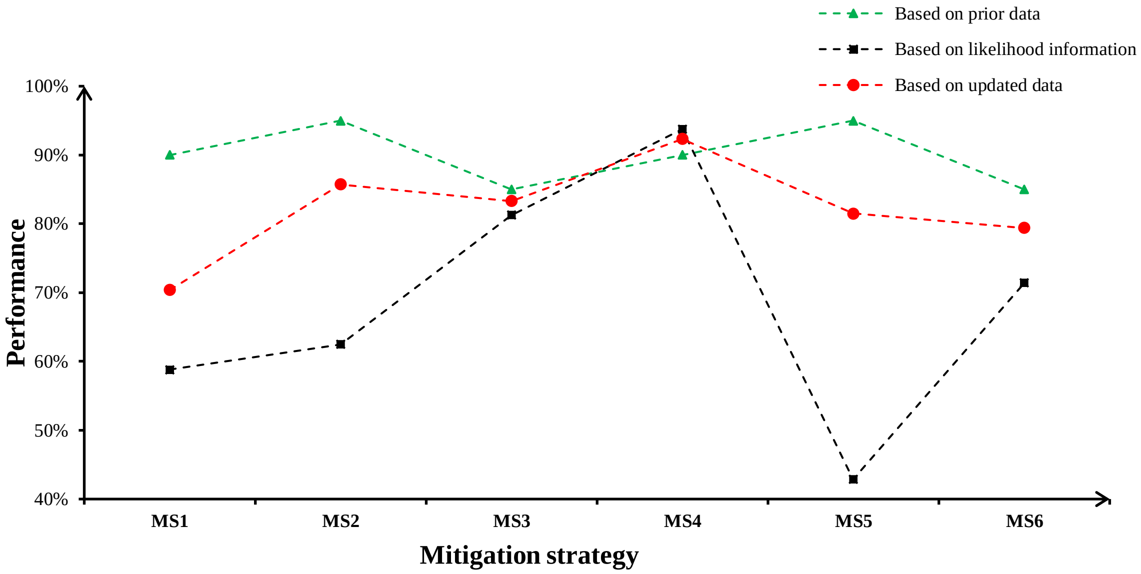


Figure 5.16. The performance of current employed mitigation strategies using prior, likelihood, and posterior data.

In the ***third step***, the expected exposure to tolerance-related risks will be updated using the revised performance values of the mitigation strategies. The results of the Monte Carlo analysis after running 10,000 iterations at an 80% confidence level (i.e., 80th percentile) revealed that the total expected risk impact is $32,460 (i.e., the expected risk exposure is increased by 116% compared to the expected risk impact estimated at the static risk assessment step, due to the overall reduction in MS performance by 15% compared to the estimated performance at the static risk management step) (Figure 5.17). Figure 5.18 shows the updated risk profile after applying the revised mitigation strategies' performance.

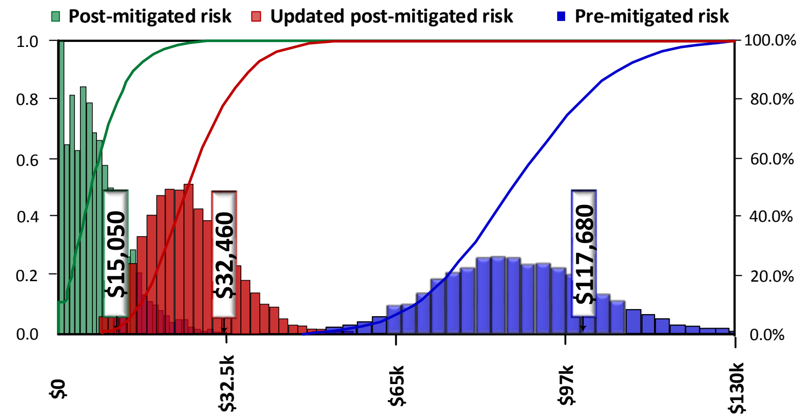


Figure 5.17. shows the increase in the total expected risks' exposure after employing the revised performance-values of MSs.

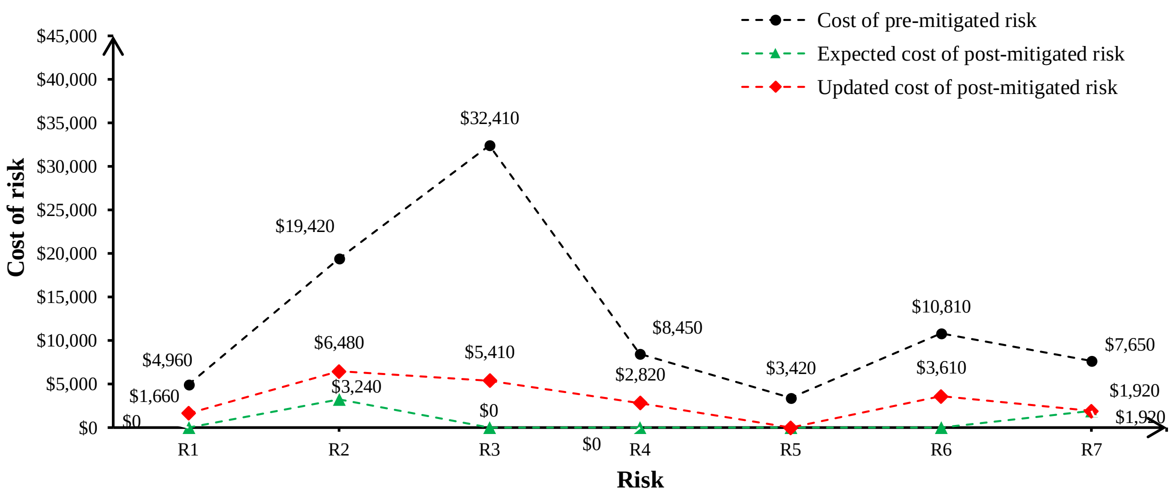


Figure 5.18. The updated risk profile after applying the revised mitigation strategies' performance.

It should be noted that the increase in expected risk exposure (Figure 5.17 and Figure 5.18) represents only the amount of rework cost required to fix and adjust excessive geometric variabilities in modular components at the fabrication shop. However, if these excessive geometric variabilities are detected late, for example, at the project site during the erection phase, there will be a significant amount of rework and schedule delay due to out-of-alignment and out-of-tolerance issues between modular components, which are typically resolved using reactive, expensive, and time consuming solutions (e.g., steel shims to fill the gap between the foundation and module's floor frame profile (Figure 5.19), and/or applying forces to bring modules into alignment). The current research has evaluated the impact of late detection of tolerance-related risks on some of the site-related risks such as module-to-module alignment time, module-to-site alignment time, and MEP (mechanical, electrical, and plumbing) fit-up time. The main characteristics (risk impacts) of site-related risks are estimated based on discussions with the erection team (site manager and superintendents) (Table 5.7). It worth mentioning that the probabilities of occurrence of site-related risks all have the same values as the likelihood function of risk R3 (Table 5.6), as it represents the current status of excessive geometric variabilities in the assembled modules at fabrication, which can result in the site-related risks. After running Monte Carlo analysis for 10,000 iterations and extracting the results at 80th percentile, the expected exposure of site-related risks due to late detection of excessive geometric variability issues in the modular components is \$51,160, which represents twice the expected risk impact (Figure 5.17) at the fabrication phase. Therefore, dynamic assessment and continual management of tolerance-related risks is a helpful approach for early detection of excessive geometric variabilities during fabrication processes and in preventing the aggregated and propagated impact of tolerance-related risks on site-related risks due to late detection.

Table 5.7. The expected of site-related risks due to late detection of geometric variability issues.

Site-related Risk	**Probability (%)**	**Impact**						**Exposure ($)**
		Schedule (days)			**Cost ($)**			
		Min	**Most likely**	**Max**	**Min**	**Most likely**	**Max**	
Module-to-module alignment time is increased	37.5	0.11	0.14	0.20	1,040	1,340	2,010	13,540
Module-to-site alignment time is increased	37.5	0.10	0.12	0.17	550	720	1,080	8, 020
MEP fit-up time is increased	37.5	1.10	1.20	1.80	810	1,020	1,530	29,600

Figure 5.19. Application of steel shims to fix the excessive geometric variably issues in the bottom profile of a module during assembly processes at project site.

In the ***fourth step***, risks with high impact will be identified for mitigation purposes. Based on the results of the previous step, the Risks R_1, R_2, R_3, R_4, R_6, and R_7 will be targeted for mitigation and their impact will be managed through proposing mitigation strategies that can achieve the tolerance limits (i.e., reduce excessive geometric variability issues in modular components to be within acceptable ranges). The proposed mitigation strategies are assumed to be additional to the currently inefficient MS (Table 5.8). The cost limit on additional mitigation strategies will be defined using Equation 5-5. The cost of the pre-mitigated risk impact of R_1, R_2, R_3, R_4, R_6, and R_7 is evaluated as \$113,930 based on the results of static risk assessment step (Figure 5.6), the total cost of the MSs that have an effect on these risks is estimated as \$18,300 (Table 5.4), and the updated cost of post-mitigated of these risks is assessed as \$32,460 based on the results of dynamic risk assessment step (Figure 5.18). Thus, the cost limit on additional MSs is defined as $\$113{,}930 - (\$18{,}300 + \$32{,}460)$ = \$63,170. The effectiveness and cost of the proposed additional MSs are rationally defined based on meetings with the industry partner (project manager, plant manager, project lead foreman, and modular designer) and based on the provided lessons learned documents. It should be noted that the cost of the proposed additional MSs is less than the cost limit (Table 5.8).

Table 5.8. summarizes the proposed mitigation strategies to manage tolerance-related risks' exposure.

Targeted risk	Proposed MS	MS type	MS cost	Manageability
R1 & R2	**MS1:** Production plans should include all dimensional and geometric tolerances for outsourced modular components, so the labours would be aware of acceptable geometric and dimensional variabilities.	Addition	$2,500	80%
	MS2: Trade foreman with high skills and experience.	Addition	$1,500	75%
	MS3: Selection of vendors with modular experience.	Addition	$5,000	20%
	MS4: Broaden the vendor's involvement with fabrication and assembly team to produce better integrated modular solutions.	Addition	$8,000	30%
	MS5: Using the same vendors in more than one project will help eliminate problems associated with outsources assemblies.	Addition	$2,000	15%
R3	**MS6:** A quality control plan needs to be developed and reviewed by project manager, plant manager, project lead foreman, and design representative at early phases of the project, to ensure the compliance between fabrication process capabilities and design tolerances.	Addition	$4,000	85%
	MS7: Hire special contractor to perform QC checks on the assembled modules.	Addition	$10,000	80%
R4	**MS8:** Implementation of none destructive tools to check the quality of welds.	Addition	$1,000	90%
	MS9: Implementation of proper welding techniques to reduce chances of incomplete penetration defects.	Addition	$500	60%
R6	**MS10:** A project specific guideline needs to be formalized and reviewed at the beginning of the project, with project manager, plant manager, and production team, to assure the current assembly equipment are free of deficiencies.	Addition	$3,000	85%
R7	**MS11:** Application of adjustable lifting frame that accounts for different modules' dimensions.	Addition	$2,000	90%
	MS12: Develop lift studies as early as possible to resolve the complications of installing unique modular assemblies.	Addition	$1,000	30%

In the ***fifth step***, the developed SFS algorithm is employed to find the optimum combination of MSs that has the biggest impact on reducing the overall risk profile. Table 5.9 summarizes the results of employing the SFS algorithm for selecting the optimum combination of mitigation strategies, which includes 6 additional MSs [MS_1, MS_6, MS_{10}, MS_8, MS_{11}, and MS_2]. It should be noted that the expected risk profile using the proposed MSs has been reduced by 89.5% compared to the updated risk profile using the currently employed MSs. Figure 5.20 illustrates the difference between post mitigated risk profile using the currently employed MSs at the fabrication shop and the expected post mitigated risk profile using the proposed mitigation strategies (revised risk management plan). The results in Figure 5.20 will give decision makers a clear risk-informed picture of the current risk profile, which can be used as one of the decision criteria to make robust, rational, and efficient modularization decisions.

Table 5.9. Results of optimum combination of MSs using SFS algorithm.

Iteration	Selected MS	MS cost ($)	Objective function value ($)	Risk reduction %	Remaining risk ($)*	Current combination of MSs	Total cost of current combination	Cost limit on MS
0	-	0	$32,460	0		-	0	$63,170
1	MS_1	$2,500	$23,300	28.2%	$3,100	$[MS_1]$	$5,600	$57,570
2	MS_6	$4,000	$14,730	26.4%	$1,510	$[MS_1,MS_6]$	$11,110	$52,060
3	MS_{10}	$3,000	$10,880	11.8%	$0	$[MS_1,MS_6,MS_{10}]$	$13,110	$49,060
4	MS_8	$1,000	$7,580	10.1%	$0	$[MS_1,MS_6,MS_{10}, MS_8]$	$14,110	$48,060
5	MS_{11}	$2,000	$4,590	9.2%	$0	$[MS_1,MS_6,MS_{10}, MS_8, MS_{11}]$	$16,110	$46,060
6	MS_2	$1,500	$3,400	3.6%	$0	$[MS_1,MS_6,MS_{10}, MS_8, MS_{11},MS_2]$	$14,610	$44,560

*****Remaining affected risks after MS cost applied

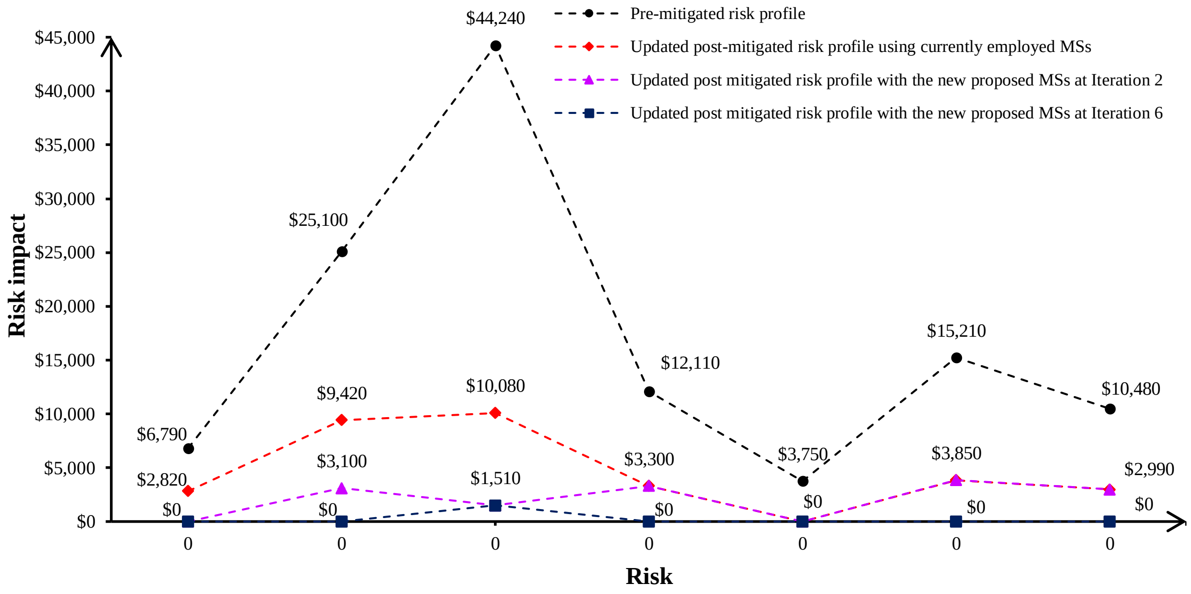


Figure 5.20. The expected risks profile using prior and revised mitigation strategies.

5.4 Conclusions

This chapter presents a dynamic and proactive methodology for the efficient management of tolerance-related risks and excessive geometric variability issues in modular construction projects. The developed methodology integrates dynamic risk assessment using Bayesian theory into classical, standard, and static quantitative risk management approaches using a probability-impact (P-I) risk model. This methodology for risk management includes a systematic process for 1) updating the initial assessment of the performance of the proposed mitigation strategies (initial risk management plans) developed during early project phases (e.g., front-end planning) using real-time data obtained during fabrication, transportation, and erection; 2) revising the tolerance-related risk profile; 3) optimizing trade-offs between investment costs and the risk of rework; and finally 4) refining risk response decisions and plans.

A modular construction case study is then used to demonstrate how the developed dynamic risk management methodology can be employed in real-world modularization projects. The results of evaluating the compliance between dimensional and geometric variabilities (D&GV) of modular components and design tolerances, using real-time data extracted mainly from fabrication and assembly processes, reveal that current modular components and assemblies experience geometric changes that, in some cases, exceeded tolerance limits (i.e., the performance of currently employed mitigation strategies is lower than the expected values estimated during the early project phases). The impact of inefficient mitigation strategies on the overall project objectives (e.g., cost and schedule) is then visualized based on an estimation of the post mitigated risk, which increased by 116%. The updated risk profile led to the proposal of a variety of (additional and replacement) mitigation strategies, which are proposed with the aim of improving the performance of the current, inefficient mitigation strategies so that tolerance requirements can be met. Finally, a cost-benefit analysis is performed in order to ensure that the revised risk management plan is economically feasible for the current case study project.

The application of the developed dynamic risk management methodology in the presented case study project demonstrates that risk management plans and risk response decisions developed during the early project phases could have been improved and their negative impact on the overall project performance might have been prevented if the dynamic risk management methodology had been applied on a continual basis during the fabrication and assembly processes for this project.

The primary contribution of this research is the development of a dynamic, proactive, and efficient risk management methodology for continually updating the proposed tolerance-based mitigation strategies using real-time, accurate, and project-specific data, in order to produce robust, appropriate, and risk-informed response decisions, all of which improve modularization performance and maximize its benefits. The dynamic risk management methodology presented also provides a systematic process for gathering, characterizing, and generating modularization process capability data for specific equipment, procedures, or processes, during the fabrication, transportation, and erection phases, which can be considered in future modular construction projects to develop design solutions that are compatible with modularization process capabilities. It is expected that the primary users and main beneficiaries of the proposed methodology will be project risk managers and modularization decision makers (e.g., designers, fabricators, and contractors) during the fabrication, transportation, and erection project phases.

Recommended directions for the continuation of this research include a rigorous analysis of all potential risks that might affect modularized projects rather than only considering tolerance-related risks and excessive geometric variabilities. This would support the decision-making process with respect to the proposal and optimum selection of efficient solutions for improving modularization performance and maximize its benefits.

Chapter 6

Summary, Conclusions, and Recommendations

6.1 Summary

Managing tolerance-related risks and excessive geometric variability issues in modular components and assemblies represents a major challenge in construction projects due to inefficient identification of optimum geometric variability (i.e., tolerances), negative effects of overall accumulation of as-built deviations on the aggregated and assembled structure onsite, and lack of accurate data on modularization process capability for fabrication, transportation, and erection project phases. Numerous decision support systems (DSSs) and toolkits that have been developed to assist decision makers with their evaluation of the potential benefits and advantages of the use of modularization as a building method in construction projects. However, most previously developed modularization DSSs and toolkits focus on: strategic and high-level decisions; general modularization risks (e.g., market demand, environmental impact, social and political conditions, labour rates/availability/skills, material supply chain, etc.); the strict and tight tolerance notion for building modular systems and assemblies; and reactive solutions and stick-built management approaches. The existing modularization risk assessment frameworks and risk management toolkits lack a systematic process to evaluate and manage the unique relationships between tolerance-related risks (e.g., cause-effect relationships), and lack a dynamic risk assessment and management methodology to revise the risk management plans and risk response decisions when more accurate modularization process capability information becomes available.

These considerations motivated the research presented in this thesis on the development of a systematic framework and an efficient methodology for proactive, thorough, and dynamic management of tolerance-related risks and excessive geometric variability issues, which will support the modularization decision making process with respect to the optimum selection of mitigation strategies that will enhance modularization performance and maximize its benefits. The newly developed frameworks and methodologies include: 1) a systematic process for identifying the optimum geometric variability using either a strict or relaxed tolerance approach; 2) an efficient approach for thoroughly evaluating and managing tolerance-related risks at both local and global levels by employing existing methods including a probability-impact (P-I) risk model, a design structure matrix (DSM), and an analytical hierarchy process (AHP); and 3) a dynamic methodology for continually evaluating tolerance-based risk management plans and revising risk response decisions using Bayesian theory.

The developed frameworks and methodologies were then demonstrated in the main case study project, with the input from the fabrication team (project manager, modular designers, director of risk control, plant manager, and project lead foreman) and the erection team (site manager and superintendents). Several site visits were also conducted to the shop during the fabrication and assembly processes, and to the project site during the module fit-up and alignment phases of the project. The results of the applications of the developed methodologies on the case study project demonstrate that key project stakeholders and modular construction managers can efficiently reduce uncertainty in tolerance-related risk estimates and proactively manage their impact by employing the developed methodologies, to improve the performance of modularization and maximize its benefits.

6.2 Conclusions

The key contributions and associated conclusions of the work presented in this thesis are summarized as follows:

A systematic process for optimum geometric variability identification: The previously developed research studies and current modularization industry practices typically employ a strict and tight tolerance notion (i.e., tolerances that are dictated by construction codes and standards) as the only design strategy for building successful modular construction projects. However, even with application of a strict tolerance approach, out-of-alignment and out-of-tolerance issues are still one of the main notable challenges, which can result in a significant amount rework, schedule delays, and cost overruns. The current research has therefore introduced a systematic process for identifying the optimum geometric variability (using a strict or relaxed tolerance approach) by optimizing the trade-offs between the cost of early investments during design and fabrication phases, and the cost of rework during the erection phase. The results of employing the developed process will support modularization decision making process at a tactical level with respect to the optimum selection of a tolerance approach that will improve the overall cost efficiency.

A holistic framework for managing tolerance-related risks at local and global levels: Modular components and assemblies involve complex geometric interrelationships whereby excessive geometric variability in a critical component can affect the overall geometry of the aggregated and assembled structure onsite. Current modularization practices and previously developed risk management frameworks/toolkits lack a systematic methodology for quantitatively evaluating the unique relationships (i.e., propagation behaviour) among tolerance-related risks and for proactively managing their impact. The current research has therefore developed a framework for the holistic assessment and efficient management of excessive geometric variability risks at both local and global levels. The results of applying the newly developed framework will support the modularization decision making process with a better understanding of the risk profile for a project as well as new insights into the development of proactive mitigation strategies from both a local and a global perspective.

A dynamic and proactive methodology for continual management of tolerance-related risks: Lack of accurate information on modularization process capabilities for fabrication, transportation, and erection, at the early design phase, typically conveys a misleading risk status and results in suboptimal mitigation solutions, which can in turn lead to cost overruns, schedule delays, quality issues, and owner dissatisfaction. Current modularization practices and previously developed risk management frameworks apply static risk assessment and management techniques, which suffer from inability to update the generic information and initial assessment of main risk characteristics, when more realistic information becomes available. The current research has therefore presented a systematic methodology that employs Bayesian inference theory for the dynamic assessment and proactive management of excessive geometric variability issues. The application of the developed dynamic risk management methodology will support the modularization decision making process with a robust model for continually updating risk management plans and risk response decisions using real-time, accurate, and project-specific data, which will improve modularization performance and maximize its benefits. The dynamic risk management methodology presented also provides a systematic process for gathering, characterizing, and generating modularization process capability data for specific equipment, procedures, or processes, during the fabrication, transportation, and erection phases, which can be used as a baseline and used as initial input in the analysis of future modular construction projects to develop design solutions that are compatible with actual modularization process capabilities.

6.3 Limitations

While the research developed several novel aspects for the proactive and efficient management of tolerance-related risks and excessive geometric variability issues in modular construction projects, there are some limitations that still need to be addressed.

Despite demonstrating the applicability of the proposed framework for identifying optimum the tolerance approach (Chapter 3), the relaxed tolerance analysis considers hypothetical values for some of the proposed mitigation strategies based on rational assumptions. However, the exact geometric variability (i.e., relaxed tolerances) associated with each mitigation strategy should be identified based on technical specification of the proposed mitigation scenarios and based on the results of the structural analysis. In addition, confidence in the optimal mitigation action relies heavily on the accuracy of the input data for each risk (probability and expected impact), thoroughness of risk identification, and accuracy of mitigation strategy modelling (expected geometric discrepancy). A detailed understanding of the main characteristics of tolerance-related risks and performance of proposed mitigation strategies is therefore required to increase the accuracy of the analysis results.

Another limitation can be found in the proposed framework (Chapter 4) for local and global management of tolerance-related risks. From a global risk assessment perspective, adding new risks to update the risk register table following the calculation of the numerical

DSM necessitates a repetition of the global risk assessment process, which is time-consuming in practice. For this reason, thorough identification of tolerance-related risks is critical prior to the performance of the AHP pairwise comparisons.

The results of the dimensional and geometric analysis of modular components using 3D imaging technology are subject to accuracy of the alignment between point clouds and BIM models, which is typically performed manually based personal judgment. The application of automated alignment tools is therefore necessary to extract meaningful results for discrepancy quantification, and thus generate more reliable estimates of expected risks of rework, which can in turn result in more accurate risk management plans.

6.4 Recommendations for Future Research

The research developed attempts to introduce efficient risk assessment frameworks and robust risk management methodologies for tolerance-related risks and excessive geometric variability issues in modular construction projects. The limitations of this research, however, leave many opportunities for future research, which are described as follows:

Development of design-based strategies using relaxed tolerance approach: The current research considers hypothetical values for expected geometric discrepancy (relaxed tolerance values) of the proposed mitigation strategies based on rational assumptions. Further improvements and extension of the relaxed tolerance approach might include the development of more design-based strategies (e.g., material, connections, dimensions, envelopes, and assembly approaches) to encourage modularization decision makers to consider this approach as a viable solution for proactive management of excessive geometric variability issues in modular construction projects.

Implementation and refinement of relaxed tolerance approach: The concept of the relaxed tolerance approach would benefit from further validation of its ability to reduce the negative impact of excessive geometric variability issues on the overall modularization performance through application in real-world modular construction projects. Such application would provide a means to estimate the total direct and indirect costs associated with the relaxed tolerance strategy and compare it to results on other cases in which the relaxed tolerance approach was not applied to verify the efficiency and feasibility of this approach.

Development of modularization process capability data: Future research could look into the collection and evaluation of modularization process capability data for the fabrication, transportation, and erection phases, which are considered an important input for optimum selection of tolerance approach (strict or relaxed) in the design phase. Dynamic risk assessment methodology developed in this research will be useful to generate such data.

Increase the scope of integrated risks: Recommended directions for the continuation of this research include a rigorous analysis of all potential risks that might affect modularized projects rather than a focus on only tolerance-related risk. Such a shift that will enable the real complex interactions at different levels to be represented and evaluated. Such an investigation would support the proposal of more efficient solutions for improving overall modularization performance and for maximizing its benefits.

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