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Managing risk in modular construction using dimensional and geometric tolerance strategies

Yasaman Shahtaheri [a], Christopher Rausch [b], Jeffrey West [b,*], Carl Haas [b], Mohammad Nahangi [b]

[a] Charles E. Via, Jr. Department of Civil and Environmental Engineering, Patton Hall, Virginia Tech, Blacksburg, VA 24061, USA
[b] Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

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ABSTRACT

The accumulating effects of dimensional and geometric variability in modular construction have traditionally been managed using trial and error strategies and use of standardized tolerance values for similar stick-built construction scenarios. This approach often leads to site-fit rework and increase in project risk, since dimensional and geometric variability is more problematic in modular construction than stick-built construction due to module interfacing and erection on site. To address this persistent challenge within modular construction, this article presents a framework for an optimal design of dimensional and geometric variability through the use of comprehensive tolerance strategies by minimizing both fabrication costs and project risks. A methodology for developing tolerance strategies in modular construction is introduced and demonstrated using a case study on an industrial pipe chassis module. The proposed methodology links a structural analysis framework which aims to predict the performance of various assembly configurations to construction costs and various types of project risks. While structural analysis techniques mainly aim to predict failure modes and mechanisms of assemblies, this research aims to further enhance such models by adding risk and cost measures to the structural analysis models. This methodology aims to manage dimensional and geometric variability by the goal of reducing rework and decreasing project costs by providing a set of Pareto-optimal design solutions ranging from strict to lose tolerance control with respect to an amalgamated cost for module production and project risk. This allows the stakeholders, engineers and construction managers to better understand the trade-offs between fabrication costs and alignment, rework, safety, and transportation risks (in terms of cost) of modules, and therefore enhance the planning and design phases of modular construction.

1. Introduction

While traditional stick-built construction involves bringing materials and skilled crafts and trades to a site to construct a project, the use of offsite methods of construction such as prefabrication and modularization are becoming more common in *Architecture*, *Engineering*, *Construction* (AEC) projects due to numerous advantages which include shorter project schedules, lower costs, increased safety and improved quality control [8,16,19,30,36]. Despite the advantages of modular construction, several challenges exist with respect to project pre-planning, project coordination, preliminary design and transportation [4,33,45,46]. These challenges often result in limited initial design options, complex interfacing, long lead-in times, delayed planning processes, and design inflexibility which can profoundly reduce the benefits of modularization [17,24,34,43].

A major challenge in the design of modular construction projects is the management of dimensional and geometric variability, which arises from numerous sources including manufacturing processes, and flexing, warping and damage of components during transportation and installation [22]. Often the approach taken to manage dimensional and geometric variability is through the use of precise methods of production using technologies such as 3D fixturing and jig systems, laser cutting and robotic assembly. In addition to technologies which can control the amount of variability during production, 3-dimensional metrology (i.e., laser scanning) is used to inspect production compliance with specified tolerances. However, even if precise methods of production and advanced inspection technologies are used, dimensional and geometric variability can still be problematic due to discrepancies between precise production tolerances and larger site tolerances as well as geometric effects from transportation and handling loads. Despite utilizing precise production tolerances, site fitting is still often problematic, since there is less forgiveness in module geometry once on site to accommodate varying site conditions [39]. For instance, a study of two modular prefabricated high rise buildings found that the geometric inflexibility of modular units once on site was a major design limitation to selection of modular construction techniques [20]. Failure to make design considerations about geometry changes to modules can be a questionable

* Corresponding author.
E-mail address: jswest@uwaterloo.ca (J. West).

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decision as the modules move during transport and assembly, resulting in costly adjustments on site" [21]. Therefore, the management of dimensions, geometry and associated tolerances are all critical factors to successfully implement modular construction on a given project. The research described herein introduces a framework for using tolerance strategies as a means to proactively manage risk in modular construction.

2. Background

The knowledge gap filled by the proposed methodology is outlined in Fig. 1. Furthermore, Fig. 1 also highlights the general effectiveness of available methods (current methods and the proposed method) for addressing some of the challenges related to dimensional and geometric variability in modular construction. Although there are a wide range of strategies illustrated in Fig. 1 that may be employed to address dimensional and geometric variability in construction and manufacturing, none employ a risk-based approach to combine and assess the effectiveness of different strategies. The framework for risk based tolerance strategies proposed in this research is distinct from related research and current practices in this regard. The background literature section is divided into each of the key areas of related research and current practices as follows: (1) current practice of optimal modularization, (2) understanding the role of tolerances in modular construction, (3) application of tolerance theory in manufacturing, (4) application of tolerance theory in construction, (5) current approach for risk management of dimensional and geometric variability.

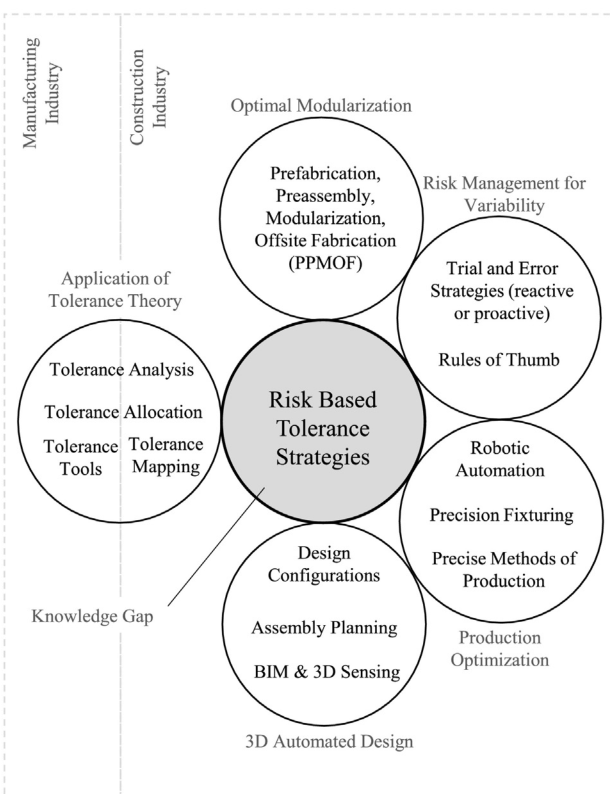
2.1. Current practice of optimal modularization

Researchers have previously developed computerized tools and score-based outlines which support the decision making process for the optimal use of prefabrication, preassembly, modularization and offsite fabrication (PPMOF) in industrial projects [40]. 3D automated design tools have been used for design configuration and assembly planning to ensure constructability, proper sequencing and identification of potential dimensional conflicts between components and systems [32]. Incurred geometrical discrepancies in parallel construction assemblies has also been captured and addressed using 3D imaging and realignment calculation techniques [31]. With respect to fabrication, the use of precision fixturing (e.g., framing tables), robotic automation, BIM and 3D sensing can help facilitate precise fabrication practices which aid in the implementation of design specifications and erection [5,25]. While these tools are valuable, they only provide a "snapshot" of expected results based on current PPMOF practices and do not provide designers with a means of making risk-based decisions to avoid rework related to the management of dimensional and geometric variability.

2.2. Understanding the role of tolerances in modular construction

Tolerances in construction can vary in magnitude from thousandths of an inch for manufactured items to several inches for field installed components [6]. While this describes AEC projects as a whole, this is also an excellent description of the range of tolerances found in modular construction, since module production tolerances can be very tight (i.e. small in magnitude), while site tolerances affecting module erection rely on stick-built construction techniques (i.e. larger tolerance magnitudes) [14,15]. As such, there are two distinct levels of precision related to the tolerances found in modular construction known as manufacturing tolerances (i.e. production of modules) and stick-built construction tolerances (i.e. erection and installation of modules).

In light of the distinct types of tolerances in modular construction, the function of tolerances in modular construction is best understood



Challenges Related to the Management of Dimensional and Geometric Variability	Avenues for Addressing Challenges: PPMOF	Trial and Error Strategies	Rules of Thumb	Robotic Automation	Precision Fixturing	Precise Methods of Production	3D Automated Design Tools	Assembly Planning	BIM & 3D Sensing	Tolerance Theory Application	Risk-Based Tolerance Strategies
Geometric conflicts between components during manufacturing		◓	◓	●	●	●	◓	◓	●	●	●
Flexing, warping and damage from transportation and handling		◓	◓			○					◓
Geometric conflicts between module and site interfaces		◓	◓			◓	◓		●	●	●
Excessive onsite assembly efforts	◓	◓	◓			○					●
Poor constructability based on geometric properties	●	◓	◓			○	●				◓
Total amount of rework associated with variability	◓										●
Total amount of cost overruns from variability	◓										●

Effectiveness: none/NA - blank, low - ○, med - ◓, high - ●

Fig. 1. Research knowledge gap (left) and effectiveness of available methods for addressing challenges related to dimensional and geometric variability as based on the literature review (right).

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