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Cutting-edge Technologies to Achieve a Higher Level of Modular Construction – Literature Review

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Abstract: Cost overruns, schedule delays, and a shortage of skilled labor are common problems the construction industry is currently experiencing. Modularization and standardization strategies have the potential to resolve the various problems mentioned above and have been applied for various construction applications for a long time. However, the level of modularization remains low, and modular construction projects have not been getting the full benefits. Thus, this review investigated the cutting-edge technologies currently being utilized to develop the modular construction field. For this paper, qualified research papers were identified using predetermined keywords from previous related research papers. Identified literature was then filtered and analyzed. According to the included reviews, several technologies are being developed for modular construction. For example, automated design and monitoring systems for modularization were developed. In addition, research labs are utilizing robotic arms for modular construction to achieve a high level of completion in the construction industry, as is seen in the manufacturing industry. Despite these efforts, more research and development are necessary because some automation technologies still require manual activities. Thus, there is great potential for further development of modularization techniques, and further research is recommended to achieve high levels of modularization.

Keywords: Critical review; Industrialized construction, Offsite construction, Automation, Robotic Arms, Simulation

1. INTRODUCTION

Modular construction is a manufacturing and installation technique that exports site-based work to offsite factories [1]. Modularization with standardization evolves from the conventional stick-built paradigm and offers innovation to the construction industry [1–3]. The modular construction technique can bring various advantages, including but not limited to improving cost and schedule performance, increasing overall productivity, improving product quality, reducing safety accidents, minimizing environmental impacts, reducing site congestion, reducing site-based permits, and improving the reliability of overall performance [4–6]. The main reason how these numerous benefits can be achieved is that the productivity of workers and robotics is more efficient in a controlled and safe, at grade, assembly/shop line-like environment such as a factory.

Past modular construction projects remained at lower levels of modularization (i.e., non-volumetric prefabrication) and failed to achieve expected levels of performance or full advantages from the modularization due to poor planning and management, design changes, late scope commitment, module shipping failure, and/or union jurisdictional problems [4,7,8]. However, recently modularization techniques have quickly developed to enable us to; 1) manage and plan a project better, 2) fabricate modules more precisely, and 3) apply the techniques to bigger and more complicated module projects [5]. Due to these developments and prevalence, modular construction techniques are highlighted as the key technology to advance the construction industry by various groups, such as professional groups, major national academic research centers, and government entities [4,9–14]. Thus, practitioners and academics in the construction industry have to pay more attention to the value of modular construction.

One critical problem of modular construction is that module fabrication and assembly are mainly conducted by human workers in the factory. Compared to the automakers (i.e., Tesla) or aircraft manufacturers (i.e., Boeing), the level of automation or robotic usage is almost zero. If the modular construction industry can innovate the module design and processes for fabrication and assembly to allow execution by robotic arms, as the automakers do, the paradigm will change, and the industry will significantly improve productivity and accomplish higher levels and more effective use of modularization. Another critical problem that the construction industry experiences is changing practitioners' stick-build paradigm to modularization. According to Razkenari et al. (2018), changing this paradigm can potentially accelerate higher levels of modularization across the industry [15].

This review paper is aimed at investigating state-of-the-art technologies and contributing to the understanding of the current situation of technologies that can be used to develop the modular construction industry. In addition, this paper presents the limitations of recent technologies and proposed future research based on them. This research is organized as follows. First, the research methodology adopted for this literature review study is outlined, including which keywords were chosen and how the literature review was conducted. Next, the literature review is summarized. Finally, conclusions and recommendations for future research directions are presented.

2. RESEARCH METHODOLOGY

To fulfill the study's objectives, a detailed literature review was focused on the leading journals that publish modular construction research. Specifically, three steps were applied to search for qualified research papers. The first was to search for journal articles using predetermined keywords, including "modular construction," "offsite construction," "modular manufacturing," "automation," "robotic arms," "simulations," "technology," "assembly," and "fabrication." These terms were chosen based on previous literature in these related fields. Papers with these specific keywords in their titles, abstracts, or keywords were considered to have fulfilled the requirements of this review paper. The search engine Google Scholar was selected to identify journals that have published the most construction related articles. The literature search was conducted in July 2020. The second step was to select appropriate papers that applied the latest modular construction technologies. After reading the abstracts of the papers selected during the first step, the papers that fit well with the topic were filtered. The last step was to summarize and compare the selected papers.

3. LITERATURE REVIEW OF HIGH TECHNOLOGY IN MODULAR CONSTRUCTION

Various kinds of cutting-edge technologies have been applied to achieve a higher level of modular construction, such as automation, simulation, and robotics. Each area has diverse research.

3.1 Automation in modularization

Various research have shown that automation brings enormous benefits to modular construction. One of the benefits is productivity improvement, but not enough quantitative methods exist with which to estimate productivity improvement. Therefore, some of the research has proposed methodologies for assessing the productivity of automated modular construction through simulation tools such as EZStrobe and lean manufacturing concept [16,17].

In the planning phase, automated modular design can achieve better construction cost performance by minimizing the time spent by designers on redundant activities during the procurement phase. Additionally, the quality of shop drawings can be improved by eliminating design assumptions and human-made errors [18]. There have been studies on automating the drafting and design for manufacturing wood-framed panels for modular buildings based on 2D CAD and parametric modeling as well as building information modeling (BIM) [19,20]. Han et al. (2012) proposed the automated visualization of modular building production lines to provide a detailed visualization model that will prevent the misreading of information and allow the production process to be understood clearly [21].

Moreover, Orlowski (2020) discussed the current status of automated manufacturing for prefabricated timber-based wall systems [22]. Unlike past methods that focused on only the structural frame and panel, the rapid advances in automation technology have been applied to most of the processes in recent years. For example, it is already possible to perform framing, stud fitting, insulation, window assembly, and storage automatically. Tamayo et al. (2020) suggested a conceptual design for controllers for automated steel wall–framing machines with the use of quality function deployment (QFD) [23]. Harichandran et al. (2019) proposed an automated monitoring system for a structural frame's state in automated modular construction based on a support vector machine (SVM), which is a machine learning technique [24].

Despite these many efforts, some activities are not fully automatic, and some processes still lack automated equivalent solutions. For instance, installing electrical conduits and window installation requires skilled laborers [22]. Thus, far more further studies are necessary to achieve a higher level of automated modularization.

3.2 Robotic arms in modularization

There are several ways to automate modular manufacturing, but robotics arms can be the best option. The automotive industry developed high-efficiency assembly lines by applying robotic arms, which are now the standard production mode of the manufacturing industry [25]. Then, several attempts have been made to apply robotic arms in modular construction. One representative case is the DFAB HOUSE, which was built by an interdisciplinary research team composed of eight ETH Zurich professorships as part of the NCCR Digital Fabrication project [26]. When the house was built, robotic arms successfully fabricated building elements directly onto the construction sites, which improved structural performance, minimized material waste, and increased worker safety. The team also used spatial timber assemblies, which is an innovative robotic prefabrication process for wood frame modules [27].

Autodesk Lab is conducting various forms of robotic fabrication research such as future workflows for robotic fabrication, collaborative robotics for construction, and flexible robot assistance on construction sites [28]. Munoz-Morera et al. (2015) proposed assembly planning for construction structures using multiple unmanned aerial systems equipped with robotic arms, and the results showed the approach's feasibility [29]. Vujovic et al. (2015) presented an innovative reconfigurable robotic system design for building construction [30]. The proposed robotic system, which was conceived on 3D printers, can easily replace various end effectors to manipulate the construction materials, assembly installation, and processing of the walls and façade.

3.3 Simulation methods in modularization

A simulation is a useful tool for discovering unforeseen bottlenecks in advance, using resources effectively, and optimizing system performance before the proposed design alters the conventional system [21]. For these purposes, simulation can be adapted to the modular construction industry, which can take advantage of simulation in various ways. Liu et al. (2019) developed a simulation model for the process of transporting and assembling modules on the construction job site for a future project that included weather and traffic conditions [31]. The research suggested proper scenarios based on the site condition or contractor's preferences. For example, if the contractor wants to improve schedule performance, the contractor can develop extra space for module storage and crane allocation.

Simulation can also improve scheduling. A simulation approach based on the lean concept was applied to enhance the productivity of modular construction and optimize the modular process [32]. Moghadam et al. (2012) developed an integrated production-line schedule model that applies BIM and lean concepts to a modular construction manufacturing system [33]. Mohamed et al. (2007) applied the general purpose simulation (GPS) method and presented a simulation-based scheduling method for pipe-spool module assembly [34]. Nasereddin et al. (2007) developed an automated approach for simulating modular housing [35].

Based on the above research, simulation can help the modular construction industry in various ways. Thus, this research will also apply the simulation technique to optimize and improve the performance of robotic arms and a smart factory.

4. CONCLUSION

Efforts to achieve high levels of modular construction have long been the subject of research in academic journals. This review paper was aimed at investigating state-of-the-art technologies in the modular construction industry. The review's results indicate that although there has been an advancement in developing techniques and tools to improve modular construction technologies, more investment in technology and innovation is necessary. For example, in some automation research, some activities were still conducted manually. It is not surprising that modularization is not a new concept, but it has recently received considerable attention and has begun to apply cutting-edge technologies, such as automation and robotic arms. Thus, there is great potential for development.

This paper makes significant contributions to the development of modular construction. There is substantial potential to develop the field, so this research can motivate researchers to apply the latest modular construction technologies in future research. In addition, this study can provide researchers with recommendations for overcoming current limitations and future research directions. For this study, the major limitation was the absence of a substantial number of studies applying high technology approaches to modular construction. This limitation arose because the topic is relatively new. Thus, further research is highly recommended. Based on this review's results, in the future, researchers should develop fully automated activities for modular construction similar to those in the manufacturing industry. In doing so, the assistance of robotic arms is likely to be indispensable.

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