MANUFACTURING OF MODULAR BUILDINGS: A LITERATURE REVIEW

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Abstract. *The recent decade has seen a growing interest in applying modular construction in high-rise buildings. However, the manufacturing of modular buildings remains slow in making technical progress and the productivity in the factory is low. The production of modules is unique and complicated as it incorporates both manufacturing features and construction trades. Whereas previous studies have proposed technologies and tools associated with design, operation and optimisation of module manufacturing systems, this field of research is currently fragmented. This paper aims to provide a systematic review of existing academic perspectives and suggest future research directions to improve module manufacturing systems. The review explores critical research issues from five aspects: process and activities, organisation and people, factory configuration, technology, and information and control system. Outlined suggestions for research opportunities include (1) increased utilisation of digital manufacturing, (2) more exploration of strategies for the adoption of automated technologies, (3) development of holistic and practical approaches to supporting DfMA methodology, (4) well-defined information management systems through BIM. The findings should contribute to a more comprehensive understanding of the practices, challenges and the state-of-the-art research in the manufacturing of modular buildings.*

Keywords: Modular building, Manufacturing, Production form, literature review.

1 INTRODUCTION

Complete modular building represents the most advanced level of offsite or prefabricated construction technologies, according to the categorisation of offsite approaches [1, 2]. As room-sized volumetric units are fully finished in the factory before being transported to designated construction sites, factory-based operations can account for approximately 70% of the overall construction activities [3]. Modular building has established itself in many countries as a practical solution to addressing housing shortage and an essential strategy for productivity enhancement in construction industries. Moreover, there have been cases of high-rise modular buildings in urban areas, e.g. the 32-storey B2 Tower in New York [4] and the 28-storey Apex House in North London [5].

Previous studies have suggested various advantages of completing modules in factory conditions including (1) more stable rate of production output, (2) higher level of quality control, (3) greater consistency and accuracy in production, (4) enhanced safety performance, (5) more opportunities for leveraging automation and information technology, and (6) decreased theft [6]. The limited production capability of module manufacturers seriously affects the efficiency and has impeded the adoption of modular construction on a large-scale [7]. Despite being similar to the assembly line of the automotive industry, module production is unique and complicated as it incorporates both manufacturing features and construction trades. Its features have been identified as fast-paced, nonlinear, labour-intensive, comprising complex procedures with a low level of standardisation, and being subject to cyclical demand [8, 9]. To date, factory-based module manufacture and assembly bear a great resemblance to the unproductive site-built activities and is slow in making technical progress.

Whereas previous studies have proposed technologies and tools associated with design, operation and optimisation of module manufacturing systems, this field of research is currently fragmented. Therefore, this paper carries out a systematic review of recent research work in respects of the manufacturing process, people requirements, factory configuration, technologies, as well as information and control systems. The study is focusing on steel module production as it is a norm in high-rise modular buildings. The objective of this study is to examine current challenges, to identify unsolved problems, and ultimately to suggest research directions for future development.

Section 2 covers theoretical framework that underpins this study. Section 3 delivers the results of a literature review on current challenges, applied techniques, corresponding findings, and research gaps. Based on the findings, a discussion on future research opportunities is presented in Section 4. A summary of this paper is in Section 5.

2 A THEORETICAL FRAMEWORK FOR LITERATURE REVIEW

A manufacturing system is defined as "*an objective-oriented network of the process through which entities flows*" [10]. Module manufacturing system presents the characteristics of manufacturing and construction. Whereas previous studies have proposed technologies and tools associated with design, operation and optimisation of module manufacturing systems, this field of research is currently limited and unorganised.

This paper aims to identify major works on module manufacturing practice, with the focus of steel-framed module manufacturing, and thereafter, to explore gaps, challenges and opportunities for future study. A literature review is applied as a valid approach by structuring and examining the recent research issues, applied approaches and corresponding findings. This review is grounded on the theoretical framework proposed by Wu [11] as presented in Figure 1.

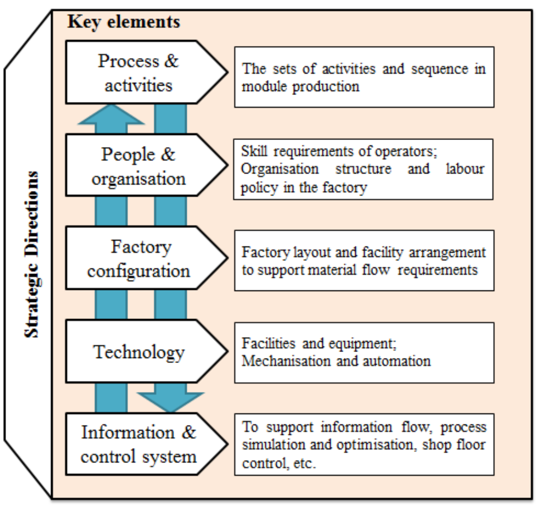

Figure 1. A theoretical framework for the review (adapted from Wu [11])

The framework begins with the strategic direction of module suppliers and incorporates five interdependent elements that are playing essential roles in module manufacturing, including the process & activities, people & organisation, factory configuration, technology, information & control system. The five elements in the factory is closely tied to module manufacturer's targeted market, commercial objective and capital investment. The manufacturing process in the context of module assembly line specifies the sets of activities and sequence to achieve the production target. Skill requirements of operators to module assembly are also crucial to production performance. Factory configuration involves factory layout and facility arrangement to support material handling requirements [7]. Technology-related elements mainly refer to the level of automation and mechanisation in the factory. Information and control system could support different tasks for facilitating workforce operating activities, such as facilitating material and information flow, process simulation and optimisation, shop floor control [12].

3 FINDINGS FROM LITERATURE REVIEW

Based on the theoretical framework, some of the key challenges in relation to the five aspects are identified from the literature review as illustrated in Table 1. Existing techniques and tools applied to solve these challenges are also outlined. The detailed discussions on the reviewed literature in terms of five elements are provided in the following subsections.

Table 1. Challenges and applied techniques for module manufacturing systems

	Challenges highlighted in recent research	Techniques/tools applied in recent research
Process	• Poorly designed material and information flow • Unbalanced distribution of workload • Floating bottlenecks • Low productivity and efficiency	• Dependency Structure Matrix • Value Stream Mapping • 5S methodology • Design for Manufacturing and Assembly (DfMA)
People & organisation	• Fragmented coordination between individual specialist groups	• Development of skill chaining
Factory configuration	• Lack of systematic approaches for facilities arrangement • Difficulties in the evaluation and verification of factory layout design	• Qualitative evaluation of layout design • Scenario analysis • Automated model development tools
Technology	• Limited use of automation	
Information and control system	• Limited use of information technology in the factory • Lack of information accuracy for module manufacture and assembly • Lack of tailored scheduling and planning tools for module manufacture • Poorly information transfer from module design phase to manufacturing phase	• DES-based modelling and simulation • Agent-based modeling • Visualization • Building Information Modeling (BIM)

3.1 Process and activities

In general, three main stages will be undertaken in the factory before module transportation, namely subassemblies manufacturing, module assembly and module completion [13]. A typical workflow of steel-framed module manufacture is illustrated in Figure 2.

Major production forms for assembling steel-framed modular units can be categorised into static and linear production systems [3]. In a static production system, groups of specialist operators move between the designated workstations where the modules to be fitted-out are placed. In linear production, modules are moved along the assembly line by rails to a set of substations where different trades are conducted by specialist workers [3]. In respects of production efficiency, static production system has an edge in producing modules with a high level of customisation while linear production is in favour of high volume of standardised modules.

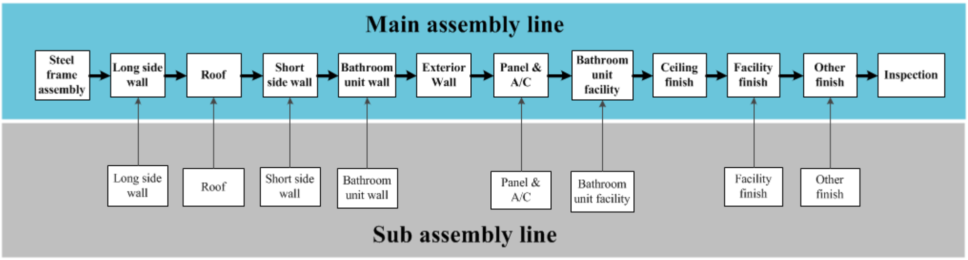

Figure 2. Typical workflow of steel-framed modules assembly (adapted from [14])

It is imperative but challenging for module manufacturers to design proper material and information flow between assembly operations and to balance workload distribution in each workstation for optimising production productivity and efficiency [7, 14]. The study of Sabharwal et al. [15] indicates that the overall production performance can be enhanced through optimised manufacture process of subassemblies. Improved output rate and reduced costs of material handling can be achieved when a series of tasks in wall and floor fabrication are restructured into a parallel workflow. The method of Dependency Structure Matrix (DSM) is utilised to modularise assembly activities in the light of information flow relationship, through which the interdependency between operations can be mitigated and production process streamlined [14, 16].

It is suggested by Mullens [7] that the workload balance within module manufacturing line is likely to be threatened by the effects of floating bottlenecks. Floating bottlenecks refer to bottleneck activities that will float between operations as changes in product mix, assembly line design and workforce arrangements occurring. Primary victims of floating bottlenecks include production time, costs, quality and efficiency. Value Stream Mapping (VSM) is a practical tool that is widely utilised in manufacturing process diagnosis, improvement and strategies analysis for future development [17, 18]. Yu's study further manifests that the adoption of 5S methodology (Sort, Straight, Shine, Standardize, Sustain) is advantageous to drive the managers and front-line workers acceptance to and involvement in Lean implementation [18]. Velarde et al. [19] proposed a simulation model to evaluate Lean techniques for different module production scenarios in order to aid decision-making on Lean strategies.

3.2 People and organisation

Current studies concerning people and organisation in the factory for modular buildings are very limited. Different strategies of skill chaining are evaluated by Arashpour et al. [20] with the purpose of recognising the optimal solution specific to different production scenario. Multi-skilled operators, who are capable of undertaking more than one trade, provides more significant opportunities for addressing workload distribution imbalance that caused by product variability [21]. Moreover, in view of the ineffective coordination between individual specialist groups, module assembly off-site is criticised as having no essential difference from its counterpart on-site [22].

3.3 Factory Configuration

The working area inside a factory usually comprises four major functional parts, including main stations, substations, and feeder area and storage place [8]. U-shaped design is one of the most efficient layouts in manufacturing industries as it provides workers more straightforward access to feeder station and facilitates inspectors checking work status along the line [8].

To efficiently support material flows and reduce the impacts of spatial constraints through factory layout improvement, systematic approaches are needed for designing and evaluating facilities arrangement. A generic framework for factory design proposed by Mehrotra et al. [23] takes the proximity between the stations and space requirements into consideration for qualitative evaluation of layout solutions. To quantitatively assess the performance of layout alternatives, a decision-making tool incorporating more critical factors from market demand, organisation, manufacturing process, material requirements to production planning for layout design is developed by Abu Hammad et al. [24]. Production rate, total cycle time, utilisation of workstations, queue times and the number of queues are used as key performance measures for evaluating the effectiveness of factory layout. The technique proposed by Nasereddin et al. [25] aims to automate the development of models for module production scenarios in order to address the technical challenges in terms of programming and verification.

3.4 Technology

Module manufacturing can be executed in three forms, i.e., (1) by pure human operators, (2) by fully automated operation, and (3) through a combination of automated operation and manual work. Introducing higher level of automation can significantly facilitate mass production and yield considerable productivity gains in the factory, while human workforce allows greater flexibility in the production system and enables a quicker response to the changing market demand. Nevertheless, pitfalls of both systems are obvious. Automation deployment requires a significant initial outlay on equipment and facilities while manual assembly stands little superiority in efficiency and productivity.

In current industrial practice, it is more likely to see a combination of human workforce and automated machinery in module manufacturing system as a balanced solution. Specialised facilities (e.g. specialised framing jig table) replace parts of manual work to build some components and subassemblies such as steel chassis, walls or floor panels [8]. Work congestion and low efficiency have been observed in this scenario, mainly because of the fragmented coordination together with the unbalanced distribution of workload. Neelamkavil suggests three prime future research directions in the manufacturing of modular construction, with the view of embracing automation in module design, material handling and the business process [26].

3.5 Information and control system

Potential benefits from BIM application in delivering volumetric modular construction projects have been reported by a good many studies [16, 22, 27]. As indicated by Lu and Korman [22], the challenges in coordinating the mechanical, electrical and pipelined (MEP) systems in modular construction can be tackled through BIM-enabled cross-disciplinary collaboration. Integrated with BIM, other technologies can play a significant role in iteratively designing and optimising manufacturing process and effectively mitigating the impacts from the constraints of space conditions, workforce availability and delivery requirements. To improve the efficiency of module manufacturing system, an integrated model named Lean-Mod are developed incorporating BIM, Lean techniques and simulation [28]. A BIM-based 4D simulation methodology developed by Lee and Kim [16] aims to manage the manufacturing process, material usage and product quality through providing high-quality shop drawings and detailed visualisation to the operators in the factory. Recent research also suggested that DfMA principles aided by BIM as being strategically crucial in delivering high-quality modules with reduced costs and shortened lead-in time [35].

Tailored tools for scheduling and planning in module manufacturing are required because mathematical analysis, heuristic approaches and commercial planning software is less capable of meeting practical demands in modular factories [16, 29]. Taghaddos [29] put forward an integrated model using DES and agent-based modelling approach for scheduling workstation and workforce in the assembly yard and for satisfying delivery timeframe in large-scale modular construction projects. The inclusion of graphical reporting function in this simulation system could support project managers in schedulingrelated decision making. The method proposed by Han et al. [30] aims to automate visualisation development from a VSM-based simulation model of module assembly process [31].

4 DISCUSSION AND OUTLOOK

The overview of recent works in section 3 shows that significant challenges exist in the manufacturing of modular buildings in respects of process & activities, people factors, factory layout, technology and information systems. Based on the highlighted challenges and existing techniques, this section discusses several research opportunities for improving the design and operation of module manufacturing systems to maximise the benefits of offsite construction.

- There have been some simulation-based tools proposed directing at supporting Lean management and improving the manufacturing systems in the modular building industry. However, further research on how to efficiently validate the proposed lean strategies or simulated outcomes before the actual application is needed. The extensive use of digital manufacturing techniques, such as Virtual Reality, should have great potential in bridging the gaps between the conceptual design and actual operations through the combination of simulation technologies and virtual presentation. For instance, workforce allocation, production scheduling and facility arrangement can be integrated through the technique of digital planning and validation [32]. In addition, digital manufacturing has been suggested as a prime research domain for the future development of engineering and management in manufacturing industries [33]. Hence, there is a need to further exploit the application of digital manufacturing in modular factories in an attempt to achieve a higher level of industrialisation and to realise full benefits from assembling modules offsite.
- Introducing automated or innovated technologies enables productivity and efficiency enhancement, quality improvement and operation costs reduction in the factory and therefore has become increasingly significant in transforming many manufacturing industries. From the review, it is found that the manufacturing of modular buildings still largely depends on manual operation with the limited adoption of automation and information technologies. We suggest that more research can be conducted to explore the potential benefits from, challenges to and strategies for increasing the use of advanced technologies, such as robotics and Internet of Things (IoT), in modular factories. For instance, there is need to develop systematic methods or tools with the purpose to identify where and how automated technologies can be adopted to enhance the manufacturing performance and to investigate how to match the level of automation with manufacturers' business aims [34].
- There is need to develop holistic and practical approaches to underpin the effective adoption of DfMA in the manufacturing of modular buildings. There are three prime approaches to best adopt DfMA, including (1) qualitative-based methods, (2) quantitative assessment through performance index, and (3) computer-aided tools and platforms [34]. However, the current adoption of DfMA in the context of modular building production largely remains theoretical and qualitative-based, making it difficult for project teams to assess and compare different module assembly solutions. Therefore, future research could explore the development of evaluation methods and tailored digital platform for strengthening the utilisation of DfMA in module manufacturing.
- An essential challenge currently facing modular building industry is the lack of information exchange standardisation for implementing BIM, which is detrimental to interoperability and collaborative design in modular building projects [36]. Previous studies on information management in modular construction include a generic data exchange framework developed by Ramaji, which is directing at the structural design tasks in multi-storey modular buildings. However, it is suggested that in future research the proposed framework should be extended with more details and specification to ensure the seamless data flow from module design phase to manufacturing phase [37].

5 CONCLUSIONS

Module suppliers are seeking ways to upgrade their manufacturing systems to improve production capability and maintain a competitive edge over traditional site-based construction. A systematic review of recent research and technologies was conducted to examine the current challenges, applied techniques and corresponding findings. The review covered five important aspects of manufacturing process & activities, people & organisation, factory configuration, technology and information & control system.

Building on the existing research to date, this paper suggests four research directions for improving the manufacturing systems of modular buildings: (1) increased utilisation of digital manufacturing, (2) more exploration of strategies for the adoption of automated technologies in the factory, (3) development of holistic and practical approaches to support DfMA methodology, (4) well-defined information management systems through BIM. The findings should contribute to a more comprehensive understanding of the practices, challenges and the state-of-the-art research in the manufacturing of modular buildings. It is also expected to support stakeholders in modular construction industry to obtain the maximum benefits from adopting modular approach for high-rise buildings.

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