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FLEXIBLE ROBOTIC PRODUCTION IN OFF-SITE CONSTRUCTION: A LEAN APPROACH

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ABSTRACT

The integration of robotics into flexible manufacturing systems (FMS) has been identified as a potential strategy for increasing modular construction flexibility. The purpose of this paper is to present a conceptual framework for investigating the relationship between FMS and robotics in modular construction. The framework proposes that by incorporating robotics into FMS, prefabricated building component manufacturing systems will gain flexibility. The two key variables of the framework are robotics (as the independent variable) and FMS (as the dependent variable). Moderator variables such as controlled environment and variability are also considered, as are mediator variables such as real-time adjustments, productivity, equipment utilization, set-up times, varying speeds, and reduced manpower. The purpose of this paper is to set the theoretical foundation for further studies on robotics integration into FMS in modular construction. The paper concludes with a discussion of the proposed implications of the framework for modular construction practitioners and researchers.

KEYWORDS

Construction 4.0, modular construction, robotics, flexible manufacturing systems.

INTRODUCTION

Modular construction is a method of manufacturing and construction that involves prefabricating building components in a controlled environment before assembling them on-site. It is based on the concept of modular product architecture, which entails designing products in such a way that they can be easily customized and configured using pre-designed modules (Bertram et al., 2019). However, the industry's main problem is a mismatch between the need of large type batch sizes in fabrication and the needs of small type batch sizes in assembly. This results in excess inventory or missed opportunities to meet customer demand, both of which can negatively impact the company. In the absence of robotics in modular construction fabrication, the industry faces one of the major challenges of manufacturing, the inability to adjust production time to meet changing demand for a product (Wadhwa, 2012).

Flexible Manufacturing Systems (FMS) is a collection of manufacturing technologies that allow for the quick and efficient production of a wide range of products in small batches. FMS technologies such as computer-controlled machining centers, automated material handling systems, and robotics are designed to work together to enable the efficient production of a wide

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range of products with minimal changeover time. FMS offers a cost-effective option for small-batch production while retaining the efficiency and productivity of mass production (Kostal et al., 2014).

The use of robotics in modular construction fabrication can help to address this issue. Robots can work around the clock by automating production processes, increasing productivity and reducing the need for manual labor. Robotics also allows for the quick and easy adjustment of production schedules to meet changing demand, making it easier to respond to market demands. Furthermore, the use of robotics can improve the consistency and accuracy of the manufacturing process, resulting in higher-quality products (Tilley, 2017).

The ability to adapt to fluctuating demands has become a critical factor for success in the 4.0 Industry era (Enrique et al., 2022). This requires production lines to be able to adapt to the demand changes. These changes in product demand occur in the market as a result of customer requirements changes (Yadav & Jayswal, 2018). The modular building industry has to deal with lean implementation challenges such as product customization flexibility and variable market demand (Innella et al., 2019). Companies must prioritize flexibility and the ability to respond quickly to changes in demand in order to remain competitive.

Despite the increased productivity brought by offsite construction involving efficiency, there is still improvement to be done. A lot of focus has been placed on using various methods for improving productivity but there have been a few emphases on incorporating automated systems into the offsite manufacturing process (Tehrani et al., 2022). The World Economic Forum has created three scenarios for the future of construction, each of which addresses a different megatrend, including the integration of robotics and pre-fabrication (Pan et al., 2022). Additionally, legislative bodies like European Parliament have emphasized the importance of robotics as a key piece for the digital transformation of the construction industry (European Parliament, 2019).

While there are challenges associated with implementing robotics in modular construction fabrication phase that is illustrated in Figure1, the benefits of increased productivity, reduced dependence on labour, improved responsiveness to changing demand, and improved product quality make it a promising technology for the future of the modular construction industry. The purpose of this paper is to present a conceptual framework for investigating the relationship between modular construction and flexible manufacturing systems (FMS). The paper also intends to provide the theoretical groundwork for future research on robotics integration into FMS in modular construction.

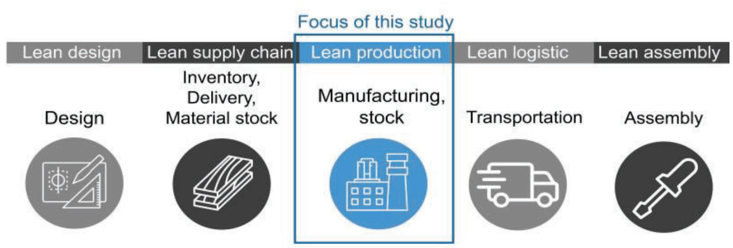

Figure 1: Production Stages in Modular Construction (Innella et al., 2019).

SYNERGIES BETWEEN FLEXIBLE MANUFACTURING SYSTEMS AND ROBOTICS

BENEFITS AND CHALLENGES OF FLEXIBLE MANUFACTURING SYSTEMS

A flexible manufacturing system (FMS) is regarded as an essential component in the realm of Industry 4.0, as it has the potential to improve system performance and thus boost the system's overall competitiveness (Priyadarshini & Gupta, 2023). As the name implies, it is characterized by its flexibility, which allows it to respond quickly to changing production requirements and conditions. An FMS is made up of adaptable machines such as robots, multi-purpose machines, or workstations, an automated transport system, and a decision-making system, also known as a scheduler, that determines which tasks will be executed and on which machine at any given time (Eloundou et al., 2015).

One of the most significant advantages of an FMS is that it allows the system to adapt to changes in demand, reducing downtime and increasing productivity (El-Khalil & Darwish, 2019). A manufacturing system's adaptability allows it to handle varying levels of product variety and quantity (Priyadarshini & Gupta, 2023). Considering that flexibility is highly important when producing for a fluctuating demand, FMS concept aims to bridge that gap. Other benefits include increased capital and equipment utilization, shorter work-in-process and set-up times, faster throughput and lead times, smaller batches and lower inventory, and fewer manpower requirements (Magalhães et al., 2022).

However, there are some challenges associated with implementing flexible manufacturing systems, such as low equipment utilization, a lack of technical expertise, and a lack of understanding on the part of senior management, all of which can have a negative impact on the FMS's implementation and execution (Priyadarshini & Gupta, 2023). Furthermore, the cost of implementing and commissioning a flexible manufacturing system is high, and the anticipated savings are difficult to quantify (Magalhães et al., 2022).

BENEFITS AND CHALLENGES OF ROBOTICS

Another key driver for Industry 4.0 is robotics (Bahrin et al., 2016), which is a rapidly growing field that has the potential to revolutionize the way products are manufactured and produced. The implementation of robots in various industries is gaining widespread recognition for its ability to improve productivity, efficiency, and reduce the need for manual labor, particularly in repetitive or hazardous tasks. Robots come in a diverse range of shapes, sizes, and functionalities, which can range from highly flexible and autonomous to being limited to performing a single or set of predetermined tasks (Smids et al., 2020).

There are two important types of robots that are relevant to this research: industrial robots and collaborative robots. Industrial robots are heavy rigid bodies that perform a complex series of actions that for a human would be very difficult and dangerous to do, such as for example carrying a huge load and are normally placed in a human-isolated workspace. On the other hand, we have collaborative robots, also known as cobots, that are smaller, more flexible and designed to operate close to humans within the same space (Sherwani et al., 2020).

The benefits of robotics in manufacturing and production are numerous. For instance, robots are capable of mass customization through the production of lots as small as single unique items because of the ability of rapidly configure machines to adapt to customer-supplied specifications. Furthermore, robots provide a high flexibility feature to the production, since they can produce new products quickly without complicated re-tooling or setup of new production lines (Bahrin et al., 2016). Additionally, robots bring the benefit of working 24/7 without breaks, leading to increased productivity and reduced downtime (Naveen Reddy et al., 2019). Furthermore, robots can perform complex tasks with a high degree of accuracy, reducing the likelihood of human error and improving product quality. Additionally, robots can work in hazardous environments, reducing the risk of injury to human workers.

However, there are also some challenges associated with the implementation of robotics technology. For instance, the high cost of acquiring and maintaining robots can be a barrier for smaller businesses, additionally the total costs are often no completely predictable during the beginning stage of the project, which might increase due to unexpected follow-up costs, for example for employee training (Flechsig et al., 2022). Moreover, the lack of technical expertise related to the operational side of the robots can limit their widespread adoption.

In conclusion, while robotics technology holds great promise for the manufacturing and production industries, it is important to carefully consider the benefits and challenges of implementing robotics, in order to maximize its impact and minimize any negative effects.

Flexible Manufacturing Systems with Robotics in Modular Construction

Modular construction has a strong connection with manufacturing as it involves the production of prefabricated building components in a controlled environment (Bertram et al., 2019). These components are then transported to the construction site and assembled, reducing the time and effort required for traditional on-site construction methods (Kamali & Hewage, 2016). This approach aligns with the principles of Industry 4.0, which prioritizes the use of advanced automation and technology to increase efficiency and quality in the manufacturing process (Bahrin et al., 2016).

Modular construction uses panels that are cut to the desired shape and size using CNC (computer numeric control) tools that can cut in almost any direction with high precision to form openings, service voids, etc. A CNC system is designed to perform specific tasks by following precise instructions. Figure 2 illustrates how the CNC system for manufacturing components for modular construction works, following a set of steps that are already programmed. However, the main drawback of this type of system is its inflexibility, since it lacks the ability to adapt to changes in its environment, modify its process, or make independent decisions (Virasak, 2019). This is the main distinction between flexible systems and a CNC sysstem.

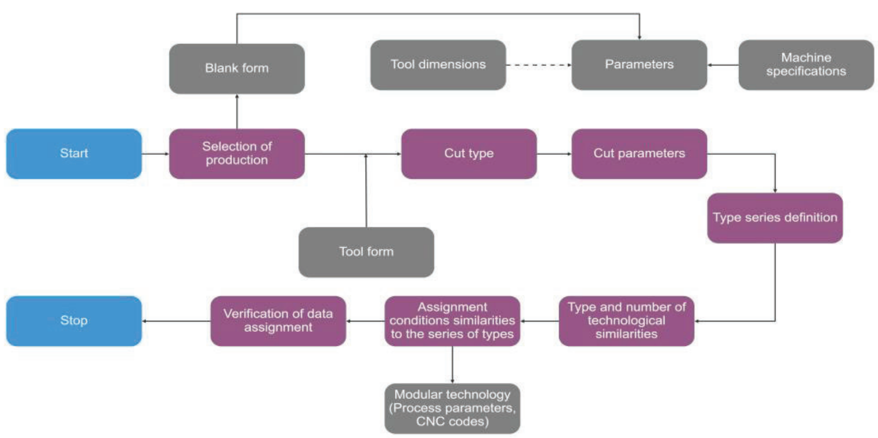

Figure 2: CNC Manufacturing Process of Modular Construction (Rząsiński, 2018).

A flexible system can alter its process, change its instructions, and make decisions based on input or feedback (Lafou et al., 2016) while a CNC only follows the instructions that have been programmed into it. On the other hand, robotics systems are considered to be more flexible compared to other manufacturing processes. One reason is robotics systems can be programmed to perform a wide range of tasks (Graetz & Michaels, 2018), making them adaptable to changing manufacturing needs. Furthermore, robotics systems often feature sensors and feedback systems that allow them to make real-time adjustments to their operations.

Production fluctuations are a common occurrence in manufacturing as illustrated in Figure 3. The graph depicts the fluctuations in demand for prefabricated components in the modular construction industry. The graph shows how demand for prefabricated components has changed over time, with peaks and troughs. Understanding these fluctuations is critical for industry stakeholders because it can help inform production, inventory management, and pricing strategies. This graph is a useful visual representation of the industry's demand patterns that can be used to represent demand fluctuations.

The demand for a manufacturing plant can vary from day to day (Ojha et al., 2013), making it unnecessary to have a 100% production capacity all the time. A low-demand rate is translated to high-demand variability, which leads to an inefficient manufacturing process as a consequence of high tooling and setup costs (Knofius et al., 2016). From a lean perspective, demand fluctuations during the production of modular construction components result in overproduction, known as an example of waste in the lean approach. Longer lead times, higher carrying costs, and extra inventory can all be the effects of overproduction (Aziz & Hafez, 2013).

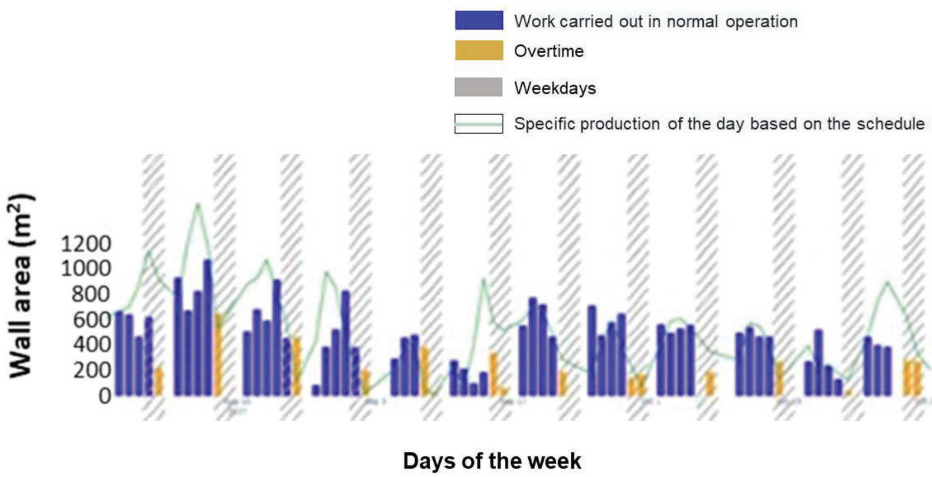

Figure 3: Fluctuation in Modular Construction Industry Demand for Prefabricated Components.

This is why flexibility in production is a key challenge in the industry. By understanding the demand variability, manufacturers can adjust their production processes to accommodate these fluctuations, reducing the need for maximum efficiency at all times. This can help save costs and resources, while still meeting customer demands. To maintain the principles of Lean, it is essential to have a flexible and responsive manufacturing system that can adjust to changing demand and avoid overproduction.

The integration of FMS with robotics in the modular construction field has several benefits. One of the main advantages we can obtain from the combination of these two, is increased production and efficiency. The use of robotics in this field enables the production process to be smoother and uninterrupted, even when faced with fluctuations, as robots can adapt to the varying speeds and production requirements. Additionally, with robotics the speed with which a product can be produced has improved, as digital designs and virtual modelling of the manufacturing process reduce the time between product design and delivery (Bahrin et al., 2016). This combination of FMS and robotics provides a powerful tool for the modular construction industry to optimize production and increase overall efficiency.

Optimization for modular construction topics has become increasingly important as the construction industry looks to build faster while also balancing the need for efficiency. In some cases, the focus on speed can be beneficial, but in many others, it may not align with the actual demand of a manufacturing plant and the variability in demand on a daily basis. Implementing flexible manufacturing systems (FMS) with robotics can address these challenges by increasing production and efficiency, allowing for adaptation to different speeds and production times as well as reducing the time between product design and delivery (Smids et al., 2020). Additionally, the integration of FMS and robotics can help to optimize operations and reduce downtime, leading to greater efficiency and cost-effectiveness (Bahrin et al., 2016)

The integration of flexible manufacturing systems (FMS) with robotics has several benefits in the field of modular construction. One of the most significant advantages of combining the two is reaching non-stop production. With the use of robotics, these can be adapted to speed changes and respond quickly to the current demand and fluctuations of the manufacturing facility, resulting in a production that is targeting the efficiency it needs.

One of the main obstacles to integrating lean in the modular construction industry is increased variability (Innella et al., 2019). FMS allows for quick adaptation to changes in demand, making it possible to handle varying levels of product variety and quantity. When combined with robotics, this flexibility becomes even more powerful, as the robots can respond quickly to changing production requirements and conditions. This leads to improved production performance, use of assets, and overall competitiveness in the market.

Moreover, the use of robotics in FMS can reduce the need for manual labor, leading to increased safety and reduced risk of injury. The integration of robotics also leads to improved equipment utilization, shorter work-in-process and set-up times, faster throughput and lead times, smaller batches and lower inventory, and reduced manpower requirements (Magalhães et al., 2022). Additionally, robotics systems can be quickly reconfigured to perform various tasks and multiple tasks (Pedersen et al., 2016), reducing the setup time and making them more flexible to handle a variety of manufacturing needs. While CNC systems are well suited for applications that require high precision and repeatability, robotics systems offer greater flexibility, programmability, and adaptability to changing manufacturing needs.

In conclusion, the combination of flexible manufacturing systems and robotics in modular construction presents numerous benefits, including increased production speed and efficiency, improved system performance and competitiveness, reduced need for manual labor, and increased safety and equipment utilization when producing panels for modular buildings. By leveraging the benefits of both FMS and robotics within modular construction, the industry should be able to better manage the fluctuations they have to face day by day and improve overall production efficiency.

CONCEPTUAL LEAN FRAMEWORK

The challenge addressed in this paper is that modular construction has a continuous change in demand, on a day-to-day basis, as is illustrated in Figure 3 which showcases an example of the variability of demand across a small period (months) for a modular construction facility. The ability to respond and adapt to changes in demand is essential to stay competitive and following lean principles. Furthermore, this variability also creates inefficiencies relating to overproduction at the system and line levels, incurring wasted efforts to deal with inventory or delays (Aziz & Hafez, 2013). Thus, a fluctuating demand requires a flexible and agile approach to production and a system that can adjust to these changes in real time is ideal to minimize wastes related to production timing.

To address this challenge, the integration of robotic flexible systems within modular construction is considered a strategic approach. A conceptual theoretical framework is developed to represent the relationship between flexible manufacturing systems (FMS) and robotics in modular construction. The focus of this study is to determine the feasibility of incorporating flexible robotics systems into modular construction processes.

A visual conceptual framework is a visual representation that outlines the key relationships among variables in a study. In such a framework, the independent variable is manipulated or changed in an experiment, the dependent variable is the variable that is being measured and is expected to change as a result of the manipulation of the independent variable. The moderator variable is a variable that influences the relationship between the independent and dependent variables, while the mediator variable is a variable that explains the relationship between the independent and dependent variables. The control variable is kept constant in an experiment to prevent it from interfering with the results and to isolate the effect of the independent variable on the dependent variable (Swaen & George, 2022).

In this conceptual framework illustrated in Figure 2. The relationship between the independent variable (robotics) and the dependent variable (modular construction flexible manufacturing systems) is understood through mediator variables. These variables act as intermediaries to explain how the independent variable impacts the dependent variable. The mediator variables selected in this framework are real-time adjustments, accuracy, equipment utilization, set-up times, varying speeds, reduced manpower, and implementation cost. These variables were selected as a result of the literature review to provide a thorough understanding of the impact of robotics on modular construction flexible manufacturing systems.

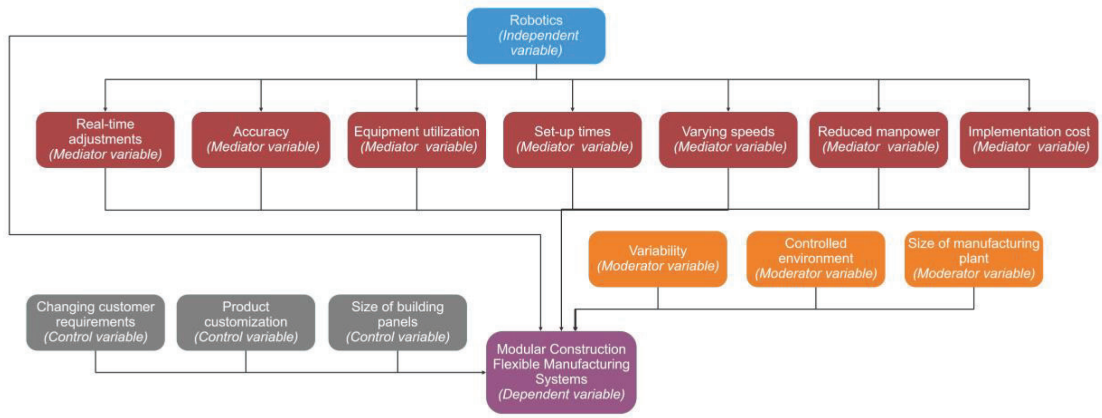

Figure 4: Conceptual Framework Robotics – Flexible Manufacturing

The selection of these specific mediator variables in the present study was based on a previous research article that established the connection between lean concepts and robotics (Cardenas et al., 2022). Specifically, the paper proposed a matrix model that described how the design parameters for a robotic cell in offsite construction interact with major lean wastes. This matrix model identified various design parameters related to robot selection criteria, production requirements, and cell requirements, which were identified through extensive literature reviews and observations of industrial robotic cells.

The variable "equipment utilization" in the framework is linked to the robot selection criteria of the matrix, as the choice of the robot can affect the efficiency and productivity of the production process. The variable "varying speeds" is linked to the production requirements of the matrix, as the speed of the production process can be affected by factors such as robot speed and cycle time. The variable "real-time adjustments" is linked to the cell requirements of the matrix, as the design of the cell and the robots used can affect the ability to make real-time adjustments to the production process. The variable "reduced manpower" in the framework may is linked to lean waste, as the use of robots can reduce the need for human labour and potentially reduce waste.

Real-time adjustments highlight the ability of robotics to make on-the-spot changes to production processes, while accuracy measures the precision of the production process. Equipment utilization, set-up times, and varying speeds demonstrate the efficiency of the production process. Reduced manpower and implementation costs provide insight into the impact of robotics on the workforce and overall cost of production. Together, these mediator variables help to illustrate the relationship between robotics and modular construction flexible manufacturing systems.

These variables have the potential to alter the level of flexibility in manufacturing systems. Variability in the manufacturing process is particularly important as it can significantly impact the flexibility feature. When variability is high, it can pose a challenge to the flexibility of manufacturing systems, whereas low variability scenarios may offer more flexibility. The level of control in the environment and the size of the manufacturing plant are also important factors that can impact the level of flexibility.

Furthermore, time is considered a control variable because it is held constant to prevent interference with the results. Although time is not the primary focus of the study, it can still impact the results. In the context of flexible manufacturing, a set period of time is used to produce a certain number of panels. However, demand can change unexpectedly, and the production process may need to be adjusted accordingly. This adjustment in production time can impact the flexibility of the system as it affects the production rate and the ability to adapt to changing demands. Hence, it is crucial to carefully manage time in flexible manufacturing systems to ensure that they remain efficient and flexible even in changing conditions.

The focus of this study is on the importance of flexibility in modular construction, as opposed to solely focusing on productivity. In the context of lean production, flexibility is valued more highly than productivity as it allows for the necessary amount to be produced at the right time. The current state of CNC systems in modular construction, which execute repetitive tasks in a fixed order and lack adaptability to changes, results in overproduction and is considered waste in the lean philosophy (Chahal & Narwal, 2017). Our proposed system offers a solution that prioritizes flexibility and the ability to produce the necessary amount at the necessary time, aligning with the principles of lean production.

CASE STUDY

This study compares the production of a cross-laminated timber (CLT) panel for modular construction using a robotic machining cell and a CNC machine. The study aims to determine which manufacturing process is more efficient and adaptable to changes in product design and production sequence.

The CLT panel has a variety of geometrical shapes for windows and doors, as well as additional features unique to CLT building techniques for modular construction. A previous robotic design for CLT machining is used to obtain simulated results (Villanueva et al., 2021), whereas the same CLT panel is then simulated in Fusion 360, illustrated in Figure 6 using a CNC machine to compare the two manufacturing processes. The specifications considered for the CNC simulation are a working area of 13500mm width, 1956mm height and 4648mm depth. Additionally, a rapid traverse speed of 63.5 MPM, cut speed of 35.5 MPM, a rapid traverse of 1.058 mm/min, max feed ratio of 0.592 mm/min, feed rate ratio of 100% and a tool change time of 15 seg.

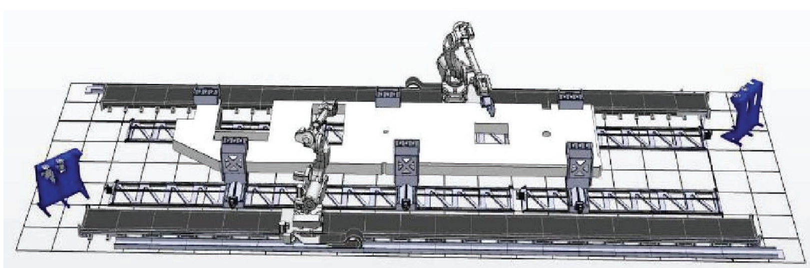

Figure 5: Robotics Simulation (taken from Villanueva et al., 2021 with permission)

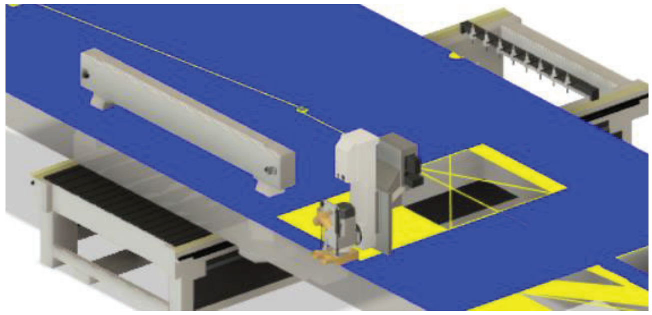

Figure 6: CNC Machining Simulation.

According to the findings of the study, the production of the CLT panel using the robotic machining cell took 18 minutes and 20 seconds (Villanueva et al., 2021), while the CNC machine took 36 minutes and 1 second to produce. The robotic machining cell is nearly twice as fast as the CNC machine, resulting in a significant difference in production time. This difference is due to the robotic machining cell's flexibility, which is programmable and adaptable, allowing it to quickly switch between different operations and make real-time adjustments. The multitasking capability of the robotic system allowed it to perform multiple operations at the same time, increasing its efficiency even further.

Assuming we have a manufacturing facility capable of producing 500 building panels per week, with a daily capacity of 100 panels. The actual demand for building panels, on the other hand, can vary greatly from day to day, so the facility must be able to adapt to changing demand. For instance, the demand for building panels is higher than expected on Monday, with a requirement of 125 panels. To meet this demand, the facility increases Monday production to 125 panels and decreases Tuesday production to 75 panels. The demand drops to 80 panels on Wednesday, so the facility adjusts its production accordingly. By the end of the week, the facility had produced 500 panels, meeting weekly demand while also being able to respond to day-to-day fluctuations in demand.

Using the information from the simulations, it is possible to produce 500 building panels per week with a daily capacity of 100 panels using the robotic machining cell. The robotic machining cell's 18 minute and 20 second production time per panel would allow the facility to produce approximately 200 panels per day, which is more than the expected daily demand of 100 panels. This provides a buffer for the facility to respond to daily fluctuations in demand. The robotic machining cell would be able to quickly adapt to the increased demand on Mondays and produce 125 panels in a single day without sacrificing panel quality. The robotic system's adaptability and flexibility allow it to quickly switch between different operations and make real-time adjustments, reducing setup time when compared to the CNC machine.

In contrast, the CNC machine, with a production time of 36 minutes per panel, would struggle to meet the increased demand on Monday. Changing tooling or setting up the machine for a new operation can be time-consuming, reducing the machine's overall flexibility and efficiency. The CNC machine's ability to respond quickly to changes in demand is limited by inflexible programming and the need for specific tooling and material options. As a result, the use of the robotic machining cell, with its quick production time and adaptability, enables the manufacturing facility to adapt to changes in demand and ensure that it can meet its production goals while remaining efficient and cost-effective. The ability to respond to changing demand is critical for any manufacturing facility's success, and the use of a robotic machining cell allows for such adaptability and efficiency.

The ability to adapt to changing demand is critical for the success of any manufacturing facility, and the use of a robotic machining cell enables such adaptability and efficiency (Javaid et al., 2022). The robotic machining cell's flexibility allows for simple process adjustments and quick adaptation to changes in product design and production sequence. This adaptability is a critical feature of a flexible manufacturing process, which is required to deal with variations in demand and product design.

As a result, the case study strongly advocates for flexibility over productivity in manufacturing processes, particularly when dealing with variations in product design and manufacturing sequence. The flexibility of the robotic machining cell over the CNC machine allows for rapid adjustment of production processes and adaptation to changes in demand and product design. The study's findings suggest that the use of robotics in manufacturing processes is an asset in the constantly changing world of industry, where the ability to respond to shifts in demand quickly and effectively is critical for success.

CONCLUSIONS

The integration of robotics into flexible manufacturing systems (FMS) in modular construction holds great promise for the future of the industry. The purpose of the paper was to present a theoretical framework for investigating the relationship between FMS and robotics in modular construction and found that the integration results in increased modular construction flexibility. The paper considered various moderator and mediator variables and concluded that a flexible manufacturing system is an essential component of Industry 4.0, with the potential to improve system performance and competitiveness.

Despite some challenges associated with the implementation of robotics in modular construction, the benefits of increased productivity, reduced dependence on labor, improved responsiveness to changing demand, and improved product quality make it a promising technology. Combining FMS with robotics in modular construction can increase production and efficiency, help to optimize operations, and reduce downtime. However, the high cost of acquiring and maintaining robots and the lack of technical expertise may limit the widespread adoption of robotics technology. To maximize the benefits of robotics integration in modular construction, it is important to carefully consider the costs and benefits and to invest in the necessary technical expertise to ensure a successful implementation.

One of the most important contributions of this study is the creation of a framework that incorporates novel mediator variables that have not previously been investigated in the context of FMS implementation. Furthermore, this study contributes to the understanding of the relationship between FMS implementation and overall manufacturing performance by emphasizing the importance of considering not only technical but also demand variability factors. While this study provides useful insights, further research is needed to understand how these mediator variables interact and how they can be effectively managed in practice.

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