Adopting Automation in Premanufacturing: A Two-Mode Network Analysis on Factors and Roles in Iran and North America's Construction Industry

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Abstract

This study embarks on an in-depth exploration of the integration of automation in premanufacturing within the construction industry, with a specific focus on contrasting the perspectives and adoption strategies in Iran and North America. Utilizing a two-mode network analysis, the research explores the complex interplay between various roles within the construction sector and a range of 27 key factors influencing the shift toward automated processes. The findings reveal distinct approaches between the two regions: Iran, at a pivotal stage of technological evolution, emphasizes foundational economic and operational efficiencies, with key factors like 'Profitability' scoring a Degree Centrality of 0.37. In contrast, North America adopts a mature, holistic approach that balances economic, operational, and environmental considerations, prioritizing 'Efficiency and Productivity' with a Degree Centrality of 0.33. This comparative analysis offers crucial insights into the differing stages of technological adoption in construction, shaped by regional market conditions and developmental phases. Furthermore, the study provides valuable guidance for policymakers and decision-makers in crafting informed strategies that accommodate specific regional needs and advancements in construction technology.

Keywords

Automation in construction; Premanufacturing, Network Analysis; Two-mode Networks; Modular Construction; Automate Premanufacturing

1 Introduction

The construction industry, an integral component of the global economy, plays a significant role in shaping Gross Domestic Product (GDP) and creating employment opportunities across the globe. It also stands as a dominant force in energy and natural resources consumption and represents a considerable share of the world's total energy use [1]. This dual impact underscores the critical need for sustainable and efficient practices within the construction domain to balance its economic contributions with environmental stewardship.

Despite its potential, the industry struggles with resource optimization, waste reduction, and the adoption of new technologies, challenges that are critical to address in today's climate-conscious world [2]. Prefabrication emerges as a key technology to address these challenges by offering benefits such as enhanced quality, speed, and sustainability in construction, alongside cost and waste reduction. However, its integration into mainstream construction practices has been met with reluctance due to inherent industry characteristics, such as the uniqueness of each project and the variability in the design and stakeholder composition [3], [4]

In this study, we explore the potential of automating the prefabrication process in the construction sector, with a particular focus on the factors influencing the choice between manual and automated premanufacturing. Manual premanufacturing relies on human labor to construct building components or entire sections off-site in a controlled factory setting before transporting them to the construction site for assembly. It is valued for its flexibility, allowing for customization and adjustments based on specific project needs or when dealing with intricate designs that automated processes cannot easily accommodate [5]. On the other hand, automated premanufacturing leverages robotics and advanced technologies to increase efficiency, precision, and safety while addressing challenges such as labor shortages and rising construction costs [6]. We investigate the technical, business, economic, and environmental drivers that play an important role in automation decisions, aspects vital for both private-sector investment and public policymaking. By conducting expert surveys in two markedly different markets, North America and Iran, and utilizing two-mode network analysis, our research not only aims to explore the dynamics among various factors but also goes beyond traditional methods to offer an in-depth understanding of their interconnectedness and relative importance within the broader system. Our approach also places a significant emphasis on the roles within the construction sector and their impact on the adoption of automation in premanufacturing. By examining the perspectives and influences of various professional roles we gain invaluable insights into the sector's diverse viewpoints on automation.

2 Background

The integration of automation in premanufacturing within the construction industry signifies a transformative shift propelled by the demands for increased efficiency, sustainability, and innovation. This review aims to synthesize the recent relevant studies in this field.

Central to this transformation is the implementation of automation throughout different construction stages, from the initial design phase to the robotic assembly. A notable example is automated modeling achieved through the integration of Building Information Modeling (BIM) with prefabrication for sustainable construction, and employing parametric design optimization to enhance design layouts for greater efficiency and lower environmental impact [7]. Additionally, the development of digital twin frameworks, as discussed in [8], [9], is a promising step toward the automation of various stages of prefabrication to enhance the adaptability of managing diverse premanufacturing projects and elements and facilitate their construction through automated processes.

The burgeoning role of Artificial Intelligence (AI) in refining the capabilities of automated robots is increasingly evident. [10] introduced a risk management system using AI algorithms to enhance the accuracy and speed of decision-making and improve the reliability and cost-effectiveness of prefabricated building projects. [11] further advanced the field by employing Deep Reinforcement Learning for automated assembly planning in robot-based construction to optimize the assembly processes through a Markov Decision Process model and advance the efficiency and safety of implementing automation in premanufacturing.

Automation in robotics assembly is another notable field of innovation and research in premanufacturing due to its potential for advancing efficiency and creative solutions. In this context, [12] demonstrated the potential of integrative robotic prefabrication and co-design methods. This research highlights the effective combination of computational design with fabrication planning and marks a significant advancement in digital automation workflows. Similarly, [13] contributed to this field by developing robotic setups that combine subtractive and additive processes to enable large-scale spatial fabrications, thereby maintaining digital accuracy and minimizing waste. Also, [14] explored efficiency gains in automated production by using simulation to optimize layout, enhance workspace utilization, and boost production. This study demonstrates automation's practical advantages in prefabrication.

The existing literature extensively explores the implementation of prefabrication in construction, including barriers, challenges, and advantages, but few studies investigate its automation. Despite technological progress, fully automating prefabrication presents complex challenges. For instance, [15] examined the complexities in timber-frame prefabrication automation to pinpoint barriers related to technology adoption, machinery sophistication, and business scale. Also, [16] outlined seven dimensions that challenge automation in modular construction, with low standardization and individual customer requests emerging among the most important barriers. Similarly, [17] highlighted key strategies to encourage automation in the Nigerian construction industry, including funding and subsidies, mandatory policies, and incentives for adoption.

These studies emphasize the complexities and potential of automating prefabrication, highlighting the need for a comprehensive approach that encompasses technical, socio-economic, regulatory, and strategic dimensions. However, their reliance on traditional data analysis may overlook the intricate interplay of influencing factors, as [16] suggests a deeper exploration into the interrelationships and dynamics of the influential factors. This study contributes by applying network analysis for a more objective, in-depth examination of automation in prefabrication, utilizing mathematical algorithms to quantify the significance of interrelated factors [18], [19]

3 Methodology

In this study, we employed a comprehensive two-mode network analysis methodology to investigate the key factors and roles influencing automation in premanufacturing. An extensive literature review meticulously analyzed over 50 papers to discern the distinctions between manual and automated premanufacturing processes in the construction industry, initially identifying over 40 potential influential factors. This preliminary set was further refined through semi-structured interviews with eight industry and academic experts from North America and Iran. These interviews aimed to evaluate the factors' relevance, clarify definitions, identify overlaps, and uncover any overlooked elements. The process ensured the factors were relevant across different construction industry contexts, particularly considering the distinctive practices between North America and Iran. This thorough examination and expert consultation ultimately streamlined the list to a focused set of 27 factors.

The complete list of final factors is as follows: (a) Factors impacting productivity and speed of the manufacturing process include complex and highly-integrated designs (F1), design flexibility and customization (F2), coordinated parallel production (F3), safety (F4), material availability (F5), faster delivery (F6), production time (F7), and smaller and modularized factories (F8); (b) Factors impacting productivity and speed of the manufacturing process encompass efficiency and productivity (F9), quality improvement (F10), the resilience of the manufacturing program (F11), long-term competitive power (F12), foreign markets (F13), profitability (F14), and unstable conditions (F15); (c) Social issues linked to or impacted by premanufacturing involve diversification of workforce (F16) and skilled workers (F17); (d) Factors related to the schedule of projects cover set-up time (F18) and long implementation lead-time (F19); (e) Overall project costs include high initial costs (F20), labor cost (F21), maintenance costs (F22), and space requirements (F23); and (f) Environmental impacts of projects comprise GHG emissions and energy saving (F24), more sustainable design (F25), noise pollution (F26), and waste reduction (F27) [20], [21], [22], [23], [24], [25], [26], [27], [6], [28], [29].

Subsequently, A survey, featuring both open and closed questions and available in English and Farsi, was distributed to firms in the construction sectors of Iran and North America. It aimed to assess perspectives on the importance and interrelations among various factors and included demographic details and familiarity with off-site construction. Considering the complex and wide-ranging nature of the factors under examination, we employed purposive sampling to engage a broad spectrum of industry stakeholders—from CEOs and university professors to general workers, to explore the relationships between each pair of factors. This scientific method allowed us to deliberately select individuals who could provide valuable insights into the relationships between each pair of factors. The survey, validated by a high Cronbach's Alpha (0.87) for reliability, also provided definitions and examples of factors to ensure clarity. To avoid neutral responses, a six-point Likert scale was utilized. Also, the questionnaire provided researchers' contact information to encourage participants to offer accurate feedback. Networks for each region were then modeled from the survey data, reflecting the diverse responses [30].

3.1 Two-mode Social Network Analysis

This study leverages a two-mode network analysis, ideal for investigating complex systems involving distinct entity categories, to examine the intricate relationships between 27 identified key factors and various stakeholders from Iran and North America. This approach offers critical insights into the systemic patterns and structures within these interactions [31].

To build the networks for our study, we first constructed adjacency matrices for role-factor relationships in each region. An adjacency matrix, a square matrix representing a finite graph, indicates the adjacency between pairs of nodes [32]—in our case, the roles and factors. In these matrices, a ‘1’ is assigned to a cell when respondents of specific roles acknowledge a factor's importance, signifying a direct relationship, while a ‘0’ indicates the absence of such recognition. These matrices not only provide detailed insights into the varying perceptions of different roles on key factors across regions but also lay the groundwork for constructing two-mode networks. In this bipartite network structure, nodes from one category (roles/stakeholders) are connected exclusively to nodes from the other category (factors), based on the stakeholders' affirmation of the factors' importance.

Upon constructing these networks, our analysis will leverage several centrality measures, namely degree, betweenness, and eigenvector centrality, to elucidate the influence and position of each node within the network, as explained in the following.

Degree Centrality (DC) reflects the number of ties a node has to other nodes, which is an indication of its activity or popularity within the network [33]. For roles, it represents how many factors they are connected to, while for factors, it shows the number of stakeholders recognizing their importance. This is crucial for identifying key factors that are widely acknowledged across different roles.

Betweenness Centrality (BC) indicates a node's capacity to act as a bridge within the network. It is calculated based on the number of shortest paths that pass through a node [33]. A high betweenness centrality for a role or factor suggests it plays a critical role in connecting various parts of the network, which can indicate stakeholders who are influential in bridging different factors or vice versa.

Eigenvector Centrality (EC) refines the basic premise of degree centrality by accounting for both the quantity and quality of a node's connections. It is based on the principle that connections to highly connected nodes contribute more to the score of the node in question [34]. Therefore, in this study, a factor with high eigenvector centrality is one that is recognized by stakeholders who themselves are widely connected or influential within the network.

4 Results and Discussion

Tables 1, 2, and 3 present the complete adjacency matrix and the results of centrality measures for selected factors (F) and roles (R) in Iran, respectively. Similarly, Tables 4 and 5 showcase the outcomes of network analysis for North America, detailing centrality measures for a subset of factors and roles. Also, Figures 1 and 2 display the two-mode networks of roles and factors for Iran and North America, respectively.

4.1 The Case of Iran

The integration of findings from the role-factor adjacency matrix and network analysis of Iran's construction industry reveals insightful trends in the perceived importance of different factors in the automation of premanufacturing processes. The adjacency matrix highlights a strong focus on key factors such as F14 (Profitability), F9 (Efficiency and Productivity), and F8 (Smaller and Modularized Factories). This pattern underscores a significant emphasis on financial viability, operational efficiency, and the adaptability of manufacturing processes within the sector.

The emphasis on profitability and efficiency in Iran's construction industry reflects a focused effort to optimize output while maintaining economic sustainability within the regional context. The focus on smaller and modularized factories, in particular, signifies a strategic shift toward more flexible, scalable production methods. This approach reflects a keen understanding of the economic and operational dynamics specific to Iran's evolving construction landscape, where cautious yet strategic steps are being taken toward modernization.

From the perspective of network measures, the equally high betweenness centrality of the mentioned factors suggests they act as key bridges in the network, connecting various aspects of the industry and facilitating the flow of influence and information. This indicates that investigation/shifts/advancements in these areas could have ripple effects, influencing a range of other connected factors and decisions within the sector.

The betweenness centrality of F15 (Unstable Conditions) and F20 (High Initial Costs) implies these factors, while not as central as the top three, are nonetheless critical in linking different areas of the industry, potentially acting as catalysts for change or areas of concern that require careful management. Their role in the network could be indicative of underlying challenges or barriers that the industry must navigate in its transition towards more automated practices.

In contrast, the lower betweenness centrality of F24 (GHG Emissions and Energy Saving) and F16 (Diversification of Workforce), coupled with their lower eigenvector centrality, suggests that these areas, while

Table 1. The Adjacency Matrix of the Role-factor Network

R \ F	1	10	11	12	13	14	15	16	17	18	19	2	20	21	22	23	24	25	26	27	3	4	5	6	7	8	9	Sum
8	0	1	1	1	1	1	1	0	1	0	0	1	1	1	1	0	0	0	0	1	0	1	0	0	1	1	1	16
1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	1	0	1	1	0	1	1	1	19
5	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	21
9	1	1	0	1	1	1	1	0	1	1	0	0	1	1	1	0	1	1	0	1	0	1	0	1	1	1	1	19
2	1	1	1	0	1	1	1	0	1	1	0	0	0	1	1	1	0	0	0	1	0	0	1	1	1	1	1	17
3	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1	0	1	0	1	1	1	19
10	0	0	0	0	1	1	1	0	1	1	1	0	1	1	1	0	1	0	0	1	0	0	1	1	1	1	1	16
7	0	1	0	0	0	1	1	0	1	1	1	0	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	16
11	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0	1	1	0	1	1	1	21
12	0	1	0	1	1	1	1	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	1	1	1	13
13	0	1	1	0	1	1	1	0	1	1	0	0	0	1	1	1	0	0	0	1	0	1	1	1	1	1	1	17
14	0	1	0	0	0	1	0	0	1	1	0	1	1	0	1	0	0	0	1	0	1	1	0	0	1	1	1	13
15	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0	1	0	0	1	1	16
6	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1	19
4	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	0	0	0	0	1	1	1	1	1	18
Sum	3	14	9	10	12	15	14	4	14	12	3	9	12	13	15	3	4	7	2	10	3	8	11	9	14	15	15	

Table 2. Centrality Measures of Selected Factors in Iran (Ranked Based on DC)

Nodes (Factors)	DC	BC	EC
F14 (Profitability)	0.3659	0.0251	0.1899
F8 (Smaller and Modularized Factories)	0.3659	0.0251	0.1899
F9 (Efficiency and Productivity)	0.3659	0.0251	0.1899
F15 (Unstable Conditions)	0.3415	0.0200	0.1808
F20 (High Initial Costs)	0.2927	0.0157	0.1511
F24 (GHG Emissions and Energy Saving)	0.0976	0.0014	0.0512
F16 (Diversification of Workforce)	0.0976	0.0013	0.0545

Table 3. Centrality Measures of Selected Roles in Iran (Ranked Based on DC)

Nodes (Roles)	DC	BC	EC
R5 (Construction Manager)	0.5122	0.0684	0.2128
R11 (University Prof)	0.5122	0.0843	0.2040
R3 (Design Engineer)	0.4634	0.0616	0.1882
R6 (Superintendent)	0.4634	0.0329	0.2045
R12 (Real Estate Developer)	0.3171	0.0141	0.1435

Table 4. Centrality Measures of Selected Factors in North America (Ranked Based on DC)

Nodes (Factors)	DC	BC	EC
F9 (Efficiency and Productivity)	0.3333	0.0205	0.1891
F14 (Profitability)	0.3333	0.0205	0.1891
F17 (Skilled Workers)	0.3077	0.0171	0.1761
F8 (Smaller and Modularized Factories)	0.3077	0.0174	0.1741
F5 (Material Availability)	0.3077	0.0170	0.1754
F10 (Quality Improvement)	0.2821	0.0136	0.1641
F24 (GHG Emissions and Energy Saving)	0.2051	0.0070	0.1174
F25 (More Sustainable Design)	0.2051	0.0068	0.1198

Table 5. Centrality Measures of Selected Roles in North America (Ranked Based on DC)

Nodes (Roles)	DC	BC	EC
R1 (Project Managers)	0.5641	0.0701	0.2344
R5 (Construction managers)	0.5641	0.0806	0.2283
R17 (Product Manager)	0.5128	0.0690	0.2022
R20 (Safety Engineers)	0.4872	0.0571	0.2007
R16 (Business Specialist)	0.4103	0.0341	0.1735

Figure 1. Two-mode network (role – factor) of Iran

Figure 2. Two-mode network (role – factor) of North America

recognized, are not yet central to the industry's main discourse or influence chains. This reflects a sector still in the early stages of integrating environmental and social considerations into its core operational strategies. However, their presence in the network hints at a growing awareness and potential for these aspects to become more integral as the industry evolves, driven by global trends and local developments in sustainability and workforce management.

Network analysis result also reveals key roles instrumental in the adoption of automation in premanufacturing by particularly highlighting Construction Managers and University Professors for their high degree and betweenness centrality. This underscores their integral role in shaping industry practices, blending technical expertise with strategic oversight. In contrast, roles with a more focused selection of factors, such as R12 (Real Estate Developer), suggest a targeted approach, reflecting specific priorities or specialized requirements within their area of the construction industry. This might indicate a concentration on aspects like investment viability and project feasibility, central to their professional domain.

The R6 (Superintendent) role, with its notable eigenvector centrality, implies a strong connection within influential networks, possibly stemming from their on-ground experience and practical insights into project execution. These insights, coupled with the moderate level of industry experience and familiarity with premanufacturing among the Iranian respondents, point towards a sector at the cusp of technological evolution. The emphasis on modularization, efficiency, and profitability highlights a transition towards more innovative, cost-effective, and adaptable construction methodologies, aligning with the sector's growing inclination towards embracing technological advancements in an increasingly competitive market.

Overall, the network analysis indicates a construction industry at a pivotal juncture, with certain factors steering current practices, while others, currently on the periphery, hold the potential to shape future directions and priorities in the Iranian context.

4.2 The Case of North America

In North America, the analysis reflects a sector that prioritizes economic sustainability, operational excellence, quality enhancement, and skilled labor. The network measures reaffirm the significance of factors such as F9 (Efficiency and Productivity), F4 (Profitability), and F17 (Skilled Workers), each demonstrating a high degree centrality. This underscores their central role in the discourse around automation which is probably influenced by the region’s advanced practices in premanufacturing and a workforce relatively familiar with these technologies. The high betweenness centrality of these factors indicates they are not just central but also serve as critical junctions within the network. Also, their significant eigenvector centrality suggests their strong interconnectedness within a network of influential factors and emphasizes their impact on the sector's decision-making processes.

Additionally, F8 (Smaller and Modularized Factories) and F5 (Material Availability) demonstrate notable betweenness centrality, revealing their capacity to link distinct parts of the network. This focus reflects an understanding of the dynamic nature of construction projects in North America and the need for responsive production methods. The attention to F10 (Quality Improvement) aligns with the region's proficiency in premanufacturing, indicating an ongoing commitment to high standards and superior outcomes.

Interestingly, F24 (GHG Emissions and Energy Saving) and F25 (More Sustainable Design), while having lower centrality measures, still reflect a growing awareness and integration of environmental sustainability within the sector. This interconnectedness indicates a sector that is progressively weaving environmental sustainability into its operational fabric, recognizing that long-term efficiency and productivity must harmoniously coexist with ecological responsibility.

These network measures paint a comprehensive picture of a region where strategic economic, operational, environmental, and human resource considerations are intricately interwoven into the fabric of the construction sector’s approach to automation. This blend of priorities, underpinned by solid technical understanding and broader societal implications, reflects a mature, forward-looking industry ready to leverage the benefits of advanced manufacturing techniques.

Regarding the roles, the network analysis reveals the prominent roles of R1 (Project Managers), R5 (Construction Managers), R17 (Product Managers), and R16 (Business Specialists) in shaping the move towards automation in premanufacturing. Their significant centrality measures indicate a deep engagement with and understanding of the industry's diverse aspects, from operational to environmental considerations.

Meanwhile, R20 (Safety Engineers), with its specific centrality measures, highlights the focus on technical and safety aspects in automation processes. This diversity in roles reflects a multifaceted approach within the industry, combining strategic management with specialized expertise. The centrality of these roles, particularly in betweenness and eigenvector measures, suggests their importance in relaying and contextualizing the industry's collective view on critical factors of automation.

4.3 Comparative Analysis of Prefabrication Automation Integration in Iran and North America

When comparing the network analyses of Iran and North America, several key insights emerge about their respective approaches to automation in premanufacturing. In Iran, the analysis reflects a sector strategically navigating its initial stages of technological integration, primarily focusing on foundational economic and operational efficiencies. This approach is characterized by a cautious yet strategic adaptation to modern methodologies, hinting at an industry gradually embracing change while considering local market dynamics and challenges.

Conversely, North America's analysis exhibits a more advanced stage of technological adoption, characterized by a holistic and integrated approach. This region demonstrates a well-rounded consideration of various factors, not just limited to immediate economic gains but also encompassing long-term sustainability and workforce development. The interplay of centrality measures in North America suggests a more interconnected and mature industry, where diverse professional roles contribute to a comprehensive understanding of automation’s broader implications.

These contrasting scenarios highlight differing priorities and stages of development in the two regions. Iran's focus on key foundational elements suggests a phase of building toward more complex integrations of automation, whereas North America's balanced approach indicates an existing advanced implementation stage, where the industry is fine-tuning and expanding its existing automated processes. This comparison offers valuable insights into how different regions adapt to technological changes in construction, shaped by their unique market conditions and developmental stages.

5 Conclusion

The comparative study of Iran and North America's construction sectors provides valuable insights into the diverse approaches and stages of adoption of automation in premanufacturing. The network analysis reveals Iran's focused strategy on economic and operational aspects, indicative of an industry preparing for more complex technological integrations. In contrast, North America's construction sector showcases an advanced stage of adoption, characterized by a well-rounded integration of automation, considering long-term sustainability alongside immediate economic benefits. This study highlights the importance of understanding regional differences in technological adoption, offering guidance for policymakers and industry stakeholders in shaping future strategies. It underscores the need for a holistic approach to integrating new technologies in construction, tailored to the unique challenges and opportunities presented by each market's stage of development and priorities.

References

[1] McKinsey, “The Next Normal in Construction,” McKinsey & Company, Jun. 2020. Accessed: May 06, 2023. [Online]. Available: https://www.mckinsey.com/~/media/mckinsey/industries/capital%20projects%20and%20infrastructure/our%20insights/the%20next%20normal%20in%20construction/executive-summary_the-next-normal-in-construction.pdf

[2] N. H. E. Omar and A. H. E. Omar, “Towards applying the global roadmap for technology development for zero energy projects,” *Int. J. Adv. Eng. Bus. Sci.*, vol. 4, no. 1, 2023.

[3] D. Hořínková, “Advantages and Disadvantages of Modular Construction, including Environmental Impacts,” in *IOP Conference Series: Materials Science and Engineering*, 2021, p. 3. Accessed: May 08, 2023. [Online]. Available: https://iopscience.iop.org/article/10.1088/1757-899X/1203/3/032002/meta

[4] S. Navaratnam, A. Satheeskumar, G. Zhang, K. Nguyen, S. Venkatesan, and K. Poologanathan, “The challenges confronting the growth of sustainable prefabricated building construction in Australia: Construction industry views,” *J. Build. Eng.*, vol. 48, p. 103935, 2022.

[5] W. Lu, K. Chen, F. Xue, and W. Pan, “Searching for an optimal level of prefabrication in construction: An analytical framework,” *J. Clean. Prod.*, vol. 201, pp. 236–245, Nov. 2018.

[6] K. Orlowski, “Automated manufacturing for timber-based panelised wall systems,” *Autom. Constr.*, vol. 109, p. 102988, 2020.

[7] S. K. Yevu, E. K. Owusu, A. P. C. Chan, K. Oti-Sarpong, I. Y. Wuni, and M. O. Tetteh, “Systematic review on the integration of building information modelling and prefabrication construction for low-carbon building delivery,” *Build. Res. Inf.*, vol. 51, no. 3, pp. 279–300, Apr. 2023, doi: 10.1080/09613218.2022.2131504.

[8] B. Kaiser, D. Littfinski, and A. Verl, “Automatic Generation of Digital Twin Models for Simulation of Reconfigurable Robotic Fabrication Systems for Timber Prefabrication,” in *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, IAARC Publications, 2021, pp. 717–724.

[9] S. Kosse, O. Vogt, M. Wolf, M. König, and D. Gerhard, “Digital twin framework for enabling

serial construction," *Front. Built Environ.*, vol. 8, p. 864722, 2022.
[10] H. Liu, Y. He, Q. Hu, J. Guo, and L. Luo, "Risk management system and intelligent decision-making for prefabricated building project under deep learning modified teaching-learning-based optimization," *PLoS One*, vol. 15, no. 7, p. e0235980, 2020.
[11] A. Zhu, T. Dai, G. Xu, P. Pauwels, B. de Vries, and M. Fang, "Deep reinforcement learning for real-time assembly planning in robot-based prefabricated construction," *IEEE Trans. Autom. Sci. Eng.*, 2023, Accessed: Dec. 04, 2023. [Online].
[12] H. J. Wagner, M. Alvarez, A. Groenewolt, and A. Menges, "Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood Pavilion," *Constr. Robot.*, vol. 4, no. 3–4, pp. 187–204, 2020.
[13] P. Eversmann, F. Gramazio, and M. Kohler, "Robotic prefabrication of timber structures: towards automated large-scale spatial assembly," *Constr. Robot.*, vol. 1, no. 1–4, pp. 49–60, 2017.
[14] E. Lachance, N. Lehoux, and P. Blanchet, "A Simulation Model to Analyze Different Automation Scenarios in a Mixed-Assembly Manufacturing Line: Timber-Frame Prefabrication Industry," *J. Constr. Eng. Manag.*, vol. 149, no. 10, p. 04023091, Oct. 2023.
[15] E. Lachance, N. Lehoux, and P. Blanchet, "Automated and robotized processes in the timber-frame prefabrication construction industry: A state of the art," in *2022 IEEE 6th International Conference on Logistics Operations Management (GOL)*, IEEE, 2022, pp. 1–10.
[16] F. G. Feldmann, "Towards Lean Automation in Construction—Exploring Barriers to Implementing Automation in Prefabrication," *Sustainability*, vol. 14, no. 19, p. 12944, 2022.
[17] A. E. Oke, J. Aliu, P. Fadamiro, P. Akanni, P. S. Jamir Singh, and M. Shaharudin Samsurijan, "Unpacking the strategies to promote the implementation of automation techniques in the construction industry," *Constr. Innov.*, 2023.
[18] D. Hevey, "Network analysis: a brief overview and tutorial," *Health Psychol. Behav. Med.*, vol. 6, no. 1, pp. 301–328, Jan. 2018, doi: 10.1080/21642850.2018.1521283.
[19] S. Letouche and B. Wille, "Connecting the Dots: Exploring Psychological Network Analysis as a Tool for Analyzing Organizational Survey Data," *Front. Psychol.*, vol. 13, p. 838093, 2022.
[20] C. P. Chea, Y. Bai, X. Pan, M. Arashpour, and Y. Xie, "An integrated review of automation and robotic technologies for structural prefabrication and construction," *Transp. Saf. Environ.*, vol. 2, no. 2, pp. 81–96, 2020.
[21] E. Dahlgren, C. Göçmen, K. Lackner, and G. Van Ryzin, "Small modular infrastructure," *Eng. Econ.*, vol. 58, no. 4, pp. 231–264, 2013.
[22] D. P. Butler, E. M. Malstrom, and S. C. Parker, "A model for the economic evaluation of automated manufacturing systems," *Cost Eng.*, vol. 38, no. 6, p. 25, 1996.
[23] A. Gunasekaran, A. R. Korukonda, I. Virtanen, and P. Yli-Olli, "Improving productivity and quality in manufacturing organizations," *Int. J. Prod. Econ.*, vol. 36, no. 2, pp. 169–183, 1994.
[24] R. Kangari and T. Yoshida, "Automation in construction," *Robot. Auton. Syst.*, vol. 6, no. 4, pp. 327–335, 1990.
[25] A. Mathur, G. S. Dangayach, M. L. Mittal, and M. K. Sharma, "Performance measurement in automated manufacturing," *Meas. Bus. Excell.*, vol. 15, no. 1, pp. 77–91, 2011.
[26] N. Viswanadham and T. L. Johnson, "Fault detection and diagnosis of automated manufacturing systems," *IFAC Proc. Vol.*, vol. 21, no. 15, pp. 95–102, 1988.
[27] A. B. Smith Jr, "Boycotts of prefabricated building products and the regulation of technological change on construction jobsites," *ILR Rev.*, vol. 25, no. 2, pp. 186–199, 1972.
[28] D. Smith, T. R. Heathman, A. Klarer, C. LeBlon, Y. Tada, and B. Hampson, "Towards automated manufacturing for cell therapies," *Curr. Hematol. Malig. Rep.*, vol. 14, pp. 278–285, 2019.
[29] C. Rosa, F. J. G. Silva, and L. P. Ferreira, "Improving the quality and productivity of steel wire-rope assembly lines for the automotive industry," *Procedia Manuf.*, vol. 11, pp. 1035–1042, 2017.
[30] S. Y. Chyung, K. Roberts, I. Swanson, and A. Hankinson, "Evidence-based survey design: The use of a midpoint on the Likert scale," *Perform. Improv.*, vol. 56, no. 10, pp. 15–23, 2017.
[31] T. Opsahl, "Triadic closure in two-mode networks: Redefining the global and local clustering coefficients," *Soc. Netw.*, vol. 35, no. 2, pp. 159–167, 2013.
[32] M. Newman, *Networks*. Oxford university press, 2018.
[33] L. C. Freeman, "Centrality in social networks: Conceptual clarification," *Soc. Netw. Crit. Concepts Sociol. Lond. Routledge*, vol. 1, pp. 238–263, 2002.
[34] P. Bonacich, "Power and centrality: A family of measures," *Am. J. Sociol.*, vol. 92, no. 5, pp. 1170–1182, 1987.