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ADVANCING THE INDUSTRIALIZATION OF CONSTRUCTION: OVERCOMING BARRIERS AND UNLOCKING BENEFITS FOR A SUSTAINABLE FUTURE

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ABSTRACT: The Industrialization of Construction (IoC) is transforming the construction industry by integrating manufacturing principles such as prefabrication, modularization, and automation to improve efficiency, reduce waste, and enhance sustainability. This paper explores the state of IoC, examining its benefits, challenges, and future potential. Through a mixed-methods approach including literature review, case studies, and industry analysis, the study identifies key drivers of IoC adoption, such as technological advancements, government policies, and increasing construction demands. Case studies of leading companies demonstrate the successful implementation of IoC technologies, highlighting innovations in digital fabrication, high-mix low-volume (HMLV) manufacturing, and robotics. However, significant barriers remain, including high initial costs, lack of standardization, skilled labor shortages, regulatory hurdles, and resistance to change. The study proposes strategic countermeasures such as industry collaboration, targeted training programs, policy reforms, and financial incentives to accelerate IoC adoption. Findings indicate that while full automation is not always necessary, selective integration of IoC technologies can yield optimal results. Additionally, balancing customization with efficiency remains a critical challenge, requiring further research and experimentation. By addressing these barriers and leveraging IoC's potential, the construction industry can achieve greater efficiency, cost-effectiveness, and sustainability. This paper provides a roadmap for industry professionals, policymakers, and researchers to advance IoC adoption and drive meaningful change in the built environment.

1. INTRODUCTION

Industrialization of construction (IoC) is not a new concept but rather an extension of historical advancements in building methods. Ancient civilizations, such as Egypt and Rome, developed construction techniques that leveraged available materials and engineering principles (Li et al. 2020; Forcael et al. 2020). The Middle Ages saw innovations like brick construction and the pointed arch, while the Industrial Revolution introduced iron, steel, and mass production techniques (Li et al. 2020). In the 20th and 21st centuries, reinforced concrete, prefabrication, and modular construction further transformed the industry, along with sustainable materials and emerging technologies such as automation and additive manufacturing (Yuan 2020). These developments have historically emerged in response to challenges like housing shortages and labor constraints, and today's wave of industrialization is driven by advancements in robotics, software, and automation.

The construction industry has historically been slow to adopt new technologies and manufacturing techniques. However, growing demands for faster, more cost-effective, and sustainable construction, coupled with increasingly complex architectural designs, are driving a shift toward IoC (Andersson & Lessing 2020). IoC applies manufacturing principles and processes to construction, integrating strategies such as standardized modular components, prefabrication, off-site manufacturing, mass customization, and automation. These approaches enhance efficiency, reduce labor and material waste, improve safety, and elevate overall construction quality.

Despite growing interest in IoC, there are still significant gaps in understanding its advancement. Much of the existing literature is concentrated on specific sectors, particularly affordable housing and building construction in developed regions, while applications in infrastructure, rural, and developing contexts remain underexplored. Additionally, there is limited research that systematically connects emerging technologies with the roles of key stakeholders in real-world implementation. This study addresses these gaps by exploring the current state of IoC and its influence on design-to-construction workflows. It aims to identify how specific technologies, stakeholder collaborations, and practical applications contribute to the adoption and scaling of IoC. By mapping these elements, the study provides a more holistic understanding of how IoC can be advanced across diverse contexts.

2. BACKGROUND

The main goal of this study is to investigate the state of practice in IoC, as well as identify areas for future growth and development. This study seeks to answer the following research question: How does the Industrialization of Construction (IoC) enable the production and integration of high-mix, low-volume components, and what opportunities does this present for advancing efficiency, customization, and sustainability across the construction sector? Furthermore, the benefits, challenges, and barriers faced by the industry in adopting HMLV manufacturing techniques are discussed. This paper presents a sample of the collected case studies as discussed in the methodology.

2.1 Definitions

IoC is defined in various ways, but it generally refers to the integration of manufacturing principles, including prefabrication, modularization, and automation, to enhance efficiency, reduce waste, and improve construction quality (Ribeirinho et al. 2020; Costa et al. 2023). While often associated with prefabrication, IoC encompasses a broader range of advanced techniques such as robotics and off-site fabrication to optimize workflows and material use. Ultimately, it is a holistic approach that applies manufacturing-inspired processes to both on-site and off-site construction, ensuring sustainability and efficiency across the architecture, engineering, and construction (AEC) industry. On the other hand, Industrialized Construction (IC) is the outcome of the IoC process, incorporating prefabrication, modular construction, additive manufacturing, and advanced materials to enhance efficiency and quality. It is defined as the use of factory-produced components that are assembled on-site, enabling faster construction, improved quality control, and cost reduction (Attouri et al. 2022). IC extends beyond prefabrication to include automation, robotics, AI, and IoT, integrating innovative techniques for optimized construction (Autodesk 2020). While IoC focuses on implementing manufacturing principles in construction, IC represents the final product of efficient, cost-effective, and sustainable buildings and infrastructure.

High-Mix, Low-Volume (HMLV) manufacturing refers to producing various products in small quantities, which is becoming increasingly relevant in construction (Wenzel 2021). Traditionally used for large-scale projects like bridges and skyscrapers, HMLV now enables the production of customized parts and components in smaller batches for more flexible, cost-effective, and efficient construction methods (Johansen et al. 2021). HMLV is essential for IoC, offering design flexibility, faster project turnaround, reduced waste, and the ability to implement complex and innovative designs, though its adoption requires changes in project planning, new systems, and worker training (Schönbeck et al. 2020; Jensen et al. 2020). Digital fabrication, particularly additive manufacturing (AM), has made significant advancements, enabling the creation of structures layer by layer from materials like steel, concrete, and polymers (Dörfler et al. 2022). AM, defined by ASTM and ISO as the process of joining materials from 3D model data layer by layer

(ASTM 2015), offers techniques such as contour crafting and concrete printing, which allow for bespoke components with minimal waste (El-Sayegh et al. 2020; Olsson et al. 2021). While it provides advantages like faster fabrication and improved surface quality, challenges include weak mechanical properties between layers, with applications range from historical reproduction to potential use in extraterrestrial construction (Xu 2017; Yeon 2018)

2.2 Benefits of IoC and Promoting Factors

The adoption of IoC techniques can bring significant benefits to the construction industry, addressing long-standing challenges such as labor shortages, rising costs, and regulatory burdens. One of the key advantages is cost savings, achieved through enhanced efficiency, waste reduction, and automation, which help lower material and labor requirements, streamline project planning, and reduce delays (Rodriguez 2021). IoC also enables enhanced customization, allowing for the production of complex, tailored building components using advanced manufacturing techniques like 3D printing, which enhances design flexibility (Ojstersek et al. 2020). Additionally, IoC can improve safety by reducing manual labor and incorporating robotics and automation, especially for hazardous tasks like material handling and demolition (Cardoso & Freschi 2022).

Sustainability is another major benefit, with IoC technologies enabling reduced waste, energy consumption, and the use of sustainable materials in construction (Ojstersek et al. 2020). IoC's ability to incorporate automation, robotics, and digital tools also enhances dexterity, scalability, and flexibility, improving construction efficiency and the ability to adapt to changing project needs (Goh & Loosemore 2017). By leveraging prefabrication and modular construction, IoC reduces waste and speeds up construction, improving efficiency and productivity while maintaining high quality and reducing delays (Lee & Chien 2020; Noghabaei et al. 2020). Furthermore, the use of technologies like BIM and digital twins optimizes design and construction processes, improving quality control and ensuring higher precision, thus reducing errors and defects (Fan & Zou 2021). Ultimately, IoC facilitates improved collaboration among project stakeholders, helping deliver better project outcomes with enhanced coordination and faster turnaround times. The integration of these advanced techniques supports the construction industry's goals of reducing costs, improving safety, enhancing sustainability, and achieving higher productivity and quality in the built environment.

The adoption of IoC techniques and technologies is rapidly increasing due to a variety of driving factors that help address key challenges in the construction industry, such as rising costs, labor shortages, and environmental concerns. One of the main drivers is environmental and sustainability concerns, with climate change pushing for more resilient, energy-efficient buildings and infrastructure. IoC methods, like prefabrication and modular construction, reduce waste and energy use, contributing to a greener construction process (Cardoso & Freschi 2022). Government policies and regulations also play a significant role in IoC adoption by offering incentives such as tax breaks and grants, along with establishing standards and investing in research and training programs (Jin et al. 2021). The increasing demand for construction, driven by population growth and urbanization, further accelerates the need for more efficient and sustainable building techniques, with IoC providing solutions to meet these rising needs (Lee & Chien 2020). Rising construction costs, including materials and labor shortages, have made it more challenging to deliver projects on time and within budget; however, IoC technologies can mitigate these pressures by improving resource utilization and reducing on-site labor requirements (Gamil et al. 2020). Skilled labor shortages in many regions are another critical factor that IoC addresses, as automation and advanced manufacturing techniques require fewer specialized skills (Moon et al. 2020). Lastly, continuous technological advancements, including robotics, 3D printing, and autonomous equipment, provide new opportunities to improve efficiency, productivity, and sustainability in construction (Yao et al. 2020). These factors collectively drive the broader implementation of IoC, helping the industry tackle its challenges and enhance overall performance.

2.3 Impeding Factors to IoC Adoption and Countermeasures of IoC and Promoting Factors

The adoption of Industrialization of Construction (IoC) technologies offers numerous benefits for the construction industry, including cost savings, efficiency, and sustainability. However, several factors impede the broader implementation of these technologies. High initial costs are a significant barrier, as companies must invest in specialized equipment and training. For example, incorporating 3D printing or robotics into construction projects requires substantial financial resources for purchasing the necessary hardware and software, in addition to upskilling workers. This investment can be daunting, particularly for smaller firms, making them hesitant to adopt IoC techniques despite their potential long-term savings (Lee & Chien 2020). Lack of regulations and outdated building codes also pose challenges. Many construction regulations do not accommodate emerging technologies like prefabrication or modular construction. Without updated standards or clear guidelines for using these advanced methods, companies may face legal uncertainties, discouraging them from adopting IoC (Rodriguez 2021). The absence of uniform standards across the industry further complicates the integration of new technologies, making it difficult for companies to evaluate and compare solutions. Without common benchmarks, firms struggle with system compatibility and may experience inefficiencies in implementing IoC methods (Demirkesen & Tezel, 2021). The shortage of skilled personnel is another critical challenge. IoC technologies require specialized knowledge and training to operate advanced machinery and maintain new systems. Many workers are not familiar with these cutting-edge tools, and training programs to address this skills gap are limited. This lack of skilled labor restricts companies from fully integrating IoC technologies, as the workforce must be adequately equipped to handle these innovations (Fan & Zou 2021).

Limited access to data and information also hampers IoC adoption. Construction professionals may not have access to detailed case studies or evidence showcasing the benefits of IoC technologies. Without clear data supporting the cost and time savings, decision-makers may be hesitant to invest in these methods (Cardoso & Freschi 2022). Moreover, inadequate infrastructure, particularly in developing regions, further impedes the adoption of IoC. Reliable electricity, internet connectivity, and transportation are necessary for technologies like 3D printing and modular construction, and their absence in certain areas limits the use of IoC (Lee & Chien 2020). Finally, resistance to change within the construction industry is a psychological barrier to adopting new technologies. Many professionals are accustomed to traditional methods and may be reluctant to shift to unfamiliar processes. Overcoming this resistance requires education, trust-building, and a cultural shift within the industry (Noghabaei et al. 2020).

To overcome the barriers to adopting IoC technologies, several countermeasures and strategies can be implemented. High initial costs can be addressed through financial incentives such as tax breaks, grants, or low-interest loans for companies transitioning to IoC methods. Collaborations with technology providers can also reduce the upfront investment burden, particularly for smaller firms. To tackle outdated building codes and regulations, industry stakeholders should work together to create updated standards and guidelines for IoC technologies. Policymakers must ensure that building codes accommodate emerging methods like modular and prefabricated construction, while fostering trust through clear, industry-wide regulations. Regarding the shortage of skilled personnel, targeted education and training programs focused on IoC technologies are essential. Universities and vocational schools can develop specialized courses to equip workers with the necessary skills, while industry-driven certification programs can standardize training. Furthermore, increasing access to data and information is vital; platforms sharing case studies, success stories, and real-world IoC examples can help construction firms make informed decisions.

Infrastructure improvements, particularly in regions lacking reliable electricity, internet connectivity, or transportation, are also necessary to support the adoption of IoC technologies. Governments and industry leaders should prioritize these developments, with public-private partnerships playing a key role in funding and promoting infrastructure upgrades. Resistance to change within the industry can be overcome by focusing on education and trust-building. Demonstrations, workshops, and pilot projects can showcase the long-term benefits of IoC technologies, while successful case studies can help ease professionals' transition to these new methods. By addressing these challenges with a multifaceted approach—financial support, regulatory updates, workforce training, better data sharing, infrastructure improvements, and effective change management—the construction industry can fully unlock the potential of IoC, leading to more efficient, sustainable, and innovative construction practices.

3. METHODOLOGY

A mixed-methods design, which combines a systematic literature review, interviews, web harvesting, and case studies, was used to achieve the research objectives. The literature review aimed to develop a comprehensive overview of existing research on the IoC and HLMV manufacturing. Searches were conducted in Scopus, Web of Science, IEEE Xplore, and Google Scholar using keywords such as industrialization of construction, industrialized construction, HMLV, automation, robotics, additive manufacturing, 3D printing, prefabrication, modular construction, and mass customization. The review focused on peer-reviewed journal articles and conference papers published between 2010 and 2023. Inclusion criteria required papers to (1) address applications or theoretical advancements in IoC, (2) focus on construction or manufacturing contexts, and (3) be published in English. Exclusion criteria eliminated duplicates, non-peer-reviewed content, and articles with minimal relevance to IoC. In addition to the literature review, web harvesting was adopted to supplement academic data with current industry practices. This method enabled the identification of companies actively implementing IoC technologies, particularly those whose innovations may not yet be documented in peer-reviewed literature. Web harvesting allowed for the collection of real-time data from company websites, press releases, and product documentation, offering a broader and more practical perspective on IoC applications. This approach was critical for capturing emerging trends, especially in the rapidly evolving domains of robotics, automation, and modular construction.

The scraped data from the web harvesting process were stored in a database for further analysis and processing. The companies identified during this phase created the sample population for which case studies were selected. The case study selection involved screening out companies that were irrelevant to this research through an in-depth exploration of their workflows. Although the case studies do not provide a complete representation of the companies deserving evaluation, they sufficiently provide a substantial amount of significant data, from which this study could infer conclusions and recommend areas for future research.

To complement the literature and industry data, semi-structured interviews were conducted with 12 professionals from companies identified through the web harvesting phase. Participants included senior engineers, operations managers, innovation directors, and executives (e.g., CTOs) who were directly involved in the planning, implementation, or oversight of IoC technologies. The semi-structured format allowed for a consistent set of guiding questions while offering flexibility to explore topics in more depth depending on each participant’s expertise. Interview topics focused on IoC implementation challenges, perceptions of HMLV manufacturing, and organizational strategies for technology adoption.

After completing the literature review process, as well as interviews, web harvesting, and site visits, a total of 160 companies were identified as companies integrating IoC technologies to an extent, some more than others. Data regarding company description, geographical location, industry, and technology applications were collected and stored in a database for an in-depth review and further analysis to determine their relevance to IoC. Figure 1 represent the geographical location of the surveyed companies. The 160 companies identified through web harvesting and industry review were geographically distributed across multiple regions. The majority were located in North America (particularly the United States), followed by companies in Asia-Pacific, Europe, and a smaller number from South America and Africa. For instance, 55 companies were identified in the U.S. alone, while only one was identified in France. This discrepancy can be attributed to a combination of factors, including the dominant use of English in online sources, the higher number of public-facing construction technology firms in the U.S., and regional differences in how IoC activities are documented or promoted online. These observations highlight both the visibility of the U.S. innovation ecosystem and the limitations of English-language web harvesting in capturing global practices.

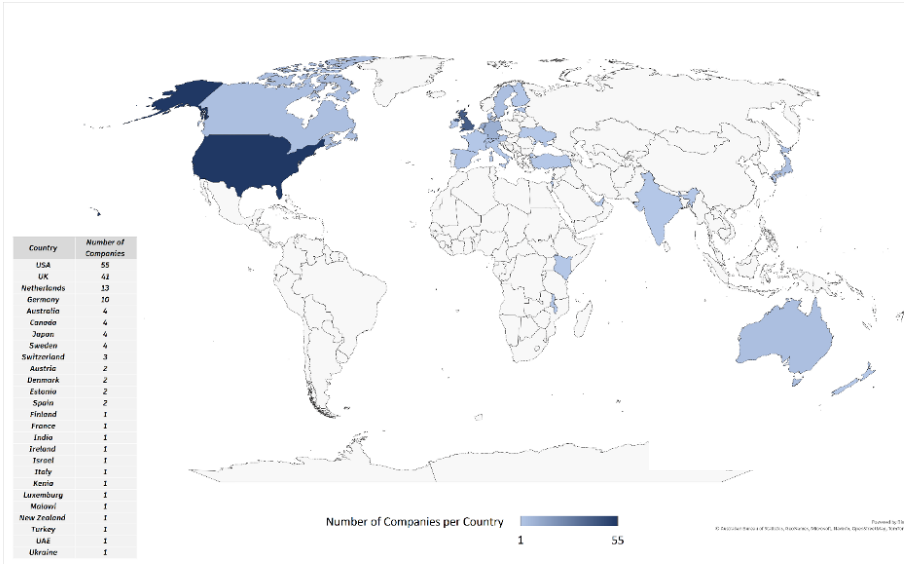

Figure 1: Representation of the companies by region

4. CASE STUDIES

These companies surveyed were classified into sectors to understand and expand the worldview of IoC across industry sectors. The sector classifications represented in this paper are Buildings and Technology. The companies categorized under the buildings sector are applying IoC techniques such as panelization and volumetric modular techniques to entire building systems, enclosures, structures, and mechanical, electrical, and plumbing (MEP) systems. The companies operate in several segments of the building sector, such as residential, commercial, institutional, industrial, public assembly, and hospitality.

The companies categorized under the technology sector, develop, and produce machinery, equipment, and other products related to IoC. Their catalog includes various products, including autonomous construction equipment, industrial machinery, robots, and advanced materials. This sector is essential for the proliferation of manufacturing techniques in construction, as it provides the tools and equipment necessary for construction companies to adopt. This sector is a large and diverse industry, with companies of all sizes operating in various markets and regions. The sector is continuously evolving with new technologies, materials, and products. Companies in this sector are constantly innovating and developing new products to meet the changing needs of the industry. Over the past few years, recent developments have occurred across these sectors. Emerging technologies in IoC are transforming the way construction is done, enabling faster completion times and improved quality control. The industry survey identified 160 companies that develop or utilize IoC technologies to some extent. Of these, 5 companies were selected as case studies to be represented in this paper.

4.1 Buildings Sector

4.1.1 Toyota Home Corporation

Toyota Home Corporation, with its head office in Nagoya, Japan, operates as an independent housing business within Toyota Motor Corporation. New built detached house construction is the main domain of the company; however, the portfolio also includes rental properties, dormitories, corporate housing, and renovation. As a division of one of the biggest automotive companies in the world, Toyota Home utilizes the know-how of car factory production to manufacture houses. Streamlined processes, advanced technologies, and well-equipped production lines, along with highly skilled workers, ensure the highest quality and reliability. Some of the techniques used by Toyota within their factory include high-precision welding used to connect steel elements for module structures is performed by automated robots and technicians working together. They also include rust-prevention method, borrowed from car manufacturing, where the entire steel frame is immersed in an electrodeposition tank filled with paint, ensures the structure is evenly coated with no gaps. Furthermore, the steel frame units are shipped with walls attached and are not worked on at the construction site meaning they are less likely to be scratched and cause rust. Similarly to cars, Toyota's marketing for houses focuses on safety and quality. Full-scale experiments are conducted to test resistance to earthquakes and aftershocks. Some of these experiments are public and shown to mass media, university professors, and industry professionals. High quality is ensured by the factory's ideal production environment and thorough inspections. The Toyota Production System (TPS), which pave the way to more generic "lean manufacturing", was developed by Toyota to reduce the effort, materials, and time in factory production. Furthermore, it allowed for highly automated flexible manufacturing, meaning smaller quantities of products with large variations, to satisfy customers' preferences. The housing division adopted the TPS and created a potential to revolutionize the housing market. Yet, despite over 40 years of building prefabricated homes, Toyota Home remains a small player within Japan's construction industry. It seems, that to be successful and impactful in IC, one need to look above and beyond the adoption of automotive manufacturing's best practices.

4.1.2 Enclos

Enclos is a leading façade contractor based in Minneapolis, Minnesota, specializing in high-performance unitized curtainwall systems. The company serves diverse markets, including high-rise office, residential, healthcare, and government projects, while also executing smaller-scale structures. Enclos' expertise lies in prefabrication and modular façade construction, ensuring its curtainwall systems meet critical requirements such as thermal, acoustic, and blast resistance, as well as accommodating building sway and seismic loads. Prefabricated modules are assembled offsite and delivered on a just-in-time basis, enabling efficient and tailored installation. Leveraging advanced technologies, Enclos enhances construction accuracy and efficiency. It employs 3D printing and prototyping for early-stage design validation, virtual construction to simulate project conditions, and parametric design for optimizing solutions. BIM plays a key role in collaboration and error reduction, while production engineering and CNC manufacturing streamline fabrication. With flexible manufacturing, Enclos can establish new assembly facilities near large projects to minimize costs and transit time. Quality assurance using metrology laser scanning ensures precise material tolerances. Enclos has been recognized for its contributions to complex architectural façade projects, receiving awards such as ENR Southwest's Specialty Contractor of the Year (2020) and ENR NY's Specialty Contractor of the Year (2017). By combining generations of expertise, innovation, and a commitment to excellence, Enclos remains at the forefront of the façade construction industry.

4.1.3 BlueScope

BlueScope is a global leader in steel materials, products, and technologies, with headquarters in Australia and operations spanning North America, New Zealand, the Pacific Islands, and Asia. The company's diverse portfolio includes Australian Steel Products, which operates the country's largest steel production facility with an annual output of approximately 3 million tonnes of crude steel. In the U.S., BlueScope Coated Products ranks as the second-largest metal painter, producing around 900,000 tonnes annually across seven facilities, mainly serving the construction industry. Meanwhile, New Zealand Steel is the nation's only fully integrated steel producer, manufacturing about 650,000 tonnes of steel each year using locally sourced iron sand and coal. BlueScope's steel products are widely used in residential, commercial, and industrial construction, including warehouses, factories, and retail spaces, as well as in manufacturing, infrastructure, agriculture, and automotive sectors. The company prioritizes innovation, tailoring its metal-coated and painted steel solutions to regional demands. Examples include COLORBOND® steel, which resists tropical discoloration, and ZINCALUME®, an aluminum-zinc alloy designed for long-term corrosion resistance in Asia's extreme climates. Additionally, TRUECORE® steel provides fire-resistant framing ideal for bushfire-prone areas. BlueScope's focus on sustainability and efficiency drives continuous product and process improvements. Innovations such as solar-reflective coatings for energy-efficient roofing and high-strength steel that minimizes material usage reflect its commitment to reducing environmental impact. The company also integrates advanced analytics and asset intelligence technology to enhance production efficiency, minimize downtime, and maintain its position at the forefront of the steel industry.

4.2 Technology Sector

4.2.1 Diamond Age

Diamond Age is a pioneering construction start-up utilizing 3D printing, robotics, and automation to combat North America's housing crisis. With a $50 million investment, they are developing "Factory in the Field," a Robotics-as-a-Service system designed to bring automation directly to construction sites. Their automation platform, featuring a suite of 26 robotic tools, aims to offset 55% of manual labor required in conventional homebuilding, introducing industrial efficiency to the job site. Key robotic attachments include a 3D print head for structural components, a subtractive tool for cutting openings, and a scanning system for as-built documentation, along with additional tools to streamline labor-intensive finishing tasks. However, Diamond Age faces significant challenges in automating home construction, including on-site equipment assembly, maneuverability after the first house is completed, efficient attachment transfers between machines, and maintaining material consistency in outdoor conditions. Additionally, precise control over robotic tools is essential for accuracy in the 3D printing process. Overcoming these challenges is crucial for their vision of revolutionizing the construction industry. Despite these hurdles, Diamond Age remains at the forefront of construction automation, offering a blend of cutting-edge technology and traditional home aesthetics to appeal to a broad market. By integrating advanced robotics and automation, they aim to redefine homebuilding, making construction faster, more efficient, and cost-effective, ultimately shaping the future of the industry.

4.2.2 House of Design

House of Design (HoD) develops dynamic automation products to make the manufacturing of building and offsite construction components safer, more efficient, and more sustainable. HoD's automated solutions include Automated Truss Systems (Roof & Floor) and Automated Offsite Construction Products (Panel Openings & Framing Assembly). The Automated Truss Systems (Roof & Floor) represent robotic solutions that increases component manufacturer's production output and capacity while helping reduce the challenges of labor shortages. Both systems require that operators place material onto the infeed conveyor, where it is fed to a pre-plate station. Once the pre-plating robot has attached the connector plates in the correct location and orientation, they are robotically assembled in the desired layout. The floor truss system requires an extra step to splice together lengths end to end. The Automated Offsite Construction Products (Panel Openings & Framing Assembly) represent robotic framing solutions for interior and exterior walls. Like the trussing systems, material needs to be loaded onto the infeed conveyor, where it is picked up by a robot and transferred to different fastening stations based on what is required. Both systems can be combined to product complete walls framing for offsite construction. HoD partnered with Autovol to produce a 400,000-sf automated housing factory, equip with 53 ABB robots to fully automate wall, ceiling and floor production that make up Autovol's volumetric modules. Each six-sided module is robotically assembled and equip all appliances, fixtures, and MEP systems, ready for shipment to site where they are assembled into larger buildings. Current production produces around 700 modules a year, with the goal to increase this to 2000.

5. CONCLUSION AND CALL TO ACTION

IoC has the potential to revolutionize the way buildings, and other structures are designed and constructed, providing numerous benefits such as increased efficiency, productivity, and sustainability. However, there are also several impediments to the broader adoption of IoC technologies, including cost, regulatory challenges, and resistance to change. To overcome these barriers, it is essential to invest in training and education, collaborate with regulators, leverage industry partnerships, demonstrate the benefits of IoC technologies, and encourage innovation. By addressing these issues, the construction industry can continue to evolve and adopt new technologies and methods that will drive progress and improve outcomes for all stakeholders. Overall, the research highlights key insights into IoC implementation. While full automation is often seen as essential, findings reveal that companies adopt varying levels of automation, emphasizing the need for a strategic approach to its application. Additionally, more research is needed on HMLV manufacturing as a tool for mass customization in construction. Finally, balancing customization with efficiency remains a challenge in HMLV construction, requiring ongoing research and dialogue to develop practical solutions that enhance production while maintaining cost-effectiveness.

The research findings presented in this study are significant in advancing our understanding of the IoC. However, it is crucial to acknowledge the limitations that may affect the generalizability of the results. First, there is knowledge gap in IoC research and practice with a disproportionate focus on the building sector and the affordable housing crisis, leaving a significant gap in understanding other areas of IoC. Second, an imbalance in literature and case studies: the majority of literature and case studies on IoC are based in developed countries, leaving a significant imbalance in the representation of this technology globally. Despite these limitations, the research provides valuable insights into the IoC and its impact. To further advance our understanding, it is essential to engage in additional research that broadens the scope of IoC knowledge across multiple sectors, including infrastructure, aging infrastructure, and the growing demand for new networks. Moreover, research should focus on the potential of IoC in rural areas and developing countries facing increased urbanization.

As the construction industry evolves, staying informed about new technologies and methods is vital for professionals to drive progress and enhance project outcomes. The adoption of IoC presents significant opportunities, but its widespread implementation requires strategic efforts from both the public and private sectors. Government investment in research, development, and incentives can accelerate IoC adoption, while industry collaboration among architects, engineers, and construction firms can facilitate knowledge-sharing and best practices. Developing training programs will help bridge the skilled labor gap, ensuring a workforce capable of implementing IoC technologies effectively. Establishing industry standards and guidelines can further streamline adoption by providing clear frameworks for companies to follow. Additionally, raising awareness of IoC's benefits can generate demand and encourage experimentation within the industry. Companies must be motivated to innovate and explore new techniques to overcome existing barriers, reduce costs, and improve efficiency. Promoting sustainability through IoC can also serve as a strong argument for its adoption, as it minimizes environmental impact and enhances resource efficiency. By fostering an environment that supports collaboration, innovation, and education, the construction industry can successfully integrate IoC and unlock its full potential, paving the way for a more efficient, cost-effective, and sustainable future.

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