

Article

Drivers towards Adopting Modular Integrated Construction for Affordable Sustainable Housing: A Total Interpretive Structural Modelling (TISM) Method

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Abstract: This study features the development of a framework to identify drivers towards increasing adoption of modular integrated construction (MiC) methods for affordable sustainable housing (ASH). The rise of offsite construction (OSC) techniques, especially MiC, has been evident in recent years. MiC's adoption in ASH is still underdeveloped; however, due to various benefits of MiC over conventional construction methods, it is envisioned to be a significant emerging approach for tackling growing housing demand, and ASH in particular. Although a few prior studies identified some factors for utilization of MiC towards ASH, studies to date have not provided a holistic review of drivers or a comprehensive framework of the interrelationships between such drivers. To address this issue, this study utilizes a three-way process including a systematic literature review, semi-structured interviews and the Total Interpretive Structure Modelling (TISM) method to study the drivers for MiC adoption in ASH. Initially, 111 drivers were extracted from a review of 40 studies in the existing literature. Following that, the significant drivers of MiC adoption for ASH were grouped into cost, time, productivity, quality, environmental, social, policy and demand. Drawing on concepts of systems thinking and graph theory, the TISM model for eight drivers was developed from both the literature review and the interview results. Four levels of hierarchy were found among drivers containing linkage, driving, depending and autonomous. Succeeding the steps of TISM and Reachability Matrix (RM) and Matrice d'Impacts Croises-Multiplication Appliquée à un Classement (MICMAC) analysis, social drivers were found to have the highest driving and lowest dependency power, followed by productivity and policy drivers. This signifies the importance of social factors for enhancing MiC adoption for ASH. In addition, a strategic framework of boosting MiC adoption in ASH is also presented, highlighting the key stakeholders and strategies for transformation along with conclusions. This study delivers a wider landscape of drivers for MiC-ASH synergy that may assist practitioners, policy makers and relevant stakeholders to better understand the relationships between the drivers.

Keywords: drivers; modular integrated construction; affordable sustainable housing; Total Interpretive Structure Modelling



Citation: Khan, A.; Yu, R.; Liu, T.; Guan, H.; Oh, E. Drivers towards Adopting Modular Integrated Construction for Affordable Sustainable Housing: A Total Interpretive Structural Modelling (TISM) Method. *Buildings* **2022**, *12*, 637. <https://doi.org/10.3390/buildings12050637>

Academic Editor: Khee Poh Lam

Received: 14 March 2022

Accepted: 5 May 2022

Published: 10 May 2022

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1. Introduction

The ever-increasing global population necessitates housing to be delivered both at a rapid pace and with consideration of sustainability attributes [1]. Many regions are facing a housing crisis that has been exacerbated by the COVID-19 pandemic, through economic factors and the decreased pace of construction operations [2]. The pandemic has plummeted the economies and growth of various nations, and a drop has occurred

in the construction of new housing across the globe [3]. Frequent pandemic restrictions have led to an adjustment of construction practices, to comply with social distancing protocols and safety of workers, which has contributed to a housing construction decline all over the world [4]. Due in part to ongoing concerns about the economic fallout caused by such pandemics, demand for affordable sustainable housing (ASH) has been further increasing [1]. The concept of affordable housing (AH) is the measure taken by government bodies to ensure that each group of income earners within the country can afford some form of housing, with the focus naturally on low- or moderate-income households [5–7]. The need for ASH is expected to become even more pressing in the near future, in light of currently unstable and fluctuating global economies [8].

Adequate housing is one of the primary and fundamental rights of human beings, as defined by the United Nations (UN) [9]. The UN's efforts in this direction are ongoing via sustainable development goals (SDGs), predominantly in the UN's SDGs #9 and #11 which are related to infrastructure and sustainable communities. The overarching aim of ASH is to deliver housing for different income groups in society in addition to maintaining social inclusion and minimizing environmental impact. While efforts are to provide ASH for all in both developed and developing countries, special attention is toward low- and middle-income residents [10]. In addition, uptake of ASH has been challenging within most developed countries such as the USA, UK and Australia [11]. The alarming need for more ASH has been highlighted by previous researchers who cite the growing population of the world which is speculated to rise from 7.9 billion in the year 2021 to 9.7 billion by the year 2050 [12]. Growing urbanization has also made it challenging for stakeholders of the construction industry to maintain a balance between demand and supply of ASH. The supply of ASH is often hindered, and may not meet requirements, as it is perceived to be low profit and thus of low interest for the private sector, which typically leaves the responsibility of developing ASH to government organizations and the public sector [13,14]. Consequently, there has been a lack of application of innovative technologies and solutions towards the development of ASH. The use of limited traditional methods of design and construction is a major barrier in achieving levels of sustainability, and is reported to be a contributor to the low deployment of ASH within communities [15,16]. More action is needed to adequately fulfil supply and demand for ASH while guaranteeing the product quality, but there is often a lack of interest among the stakeholders developing ASH.

Modular integrated construction (MiC) and other offsite construction (OSC) techniques integrated with cutting-edge technologies can not only boost the production of ASH but also maintain the sustainable and efficient nature of the output product [17–19]. However, MiC is perceived to be a costly method of construction among stakeholders; although a few studies suggest that integrating ASH with MiC will streamline the process of design, construction and operation to achieve high quality, faster output and sustainable ASH [17]. While a few studies have focused upon the pros and cons of MiC [20,21] and ASH [22–24] as an individual phenomenon, there is a gap in the literature regarding integrating MiC and other OSC techniques as an alternative approach for ASH [17]. Therefore, it is significant to categorize drivers of the implementation of MiC practices for ASH. In light of that significant gap, the primary aim of this study is to identify various drivers for implementing MiC for ASH, and to find the integration level among them by using a TISM approach. The objectives of this study are: (1) define MiC and ASH and their integration level; (2) systematically explore drivers of implementing MiC for ASH; (3) develop a TISM model to identify the interdependencies and connections of drivers; and (4) propose strategies to promote the adoption of MiC for ASH. In addition to contributing to knowledge development, the taxonomy of various drivers will provide a baseline understanding of applying MiC for ASH for relevant industry stakeholders. Thus, the novelty of this study lies not only in identifying different drivers of MiC implementation for ASH, but also in proposing strategies for effective integration at different phases of an ASH project. This study will benefit government and non-government organizations, policymakers, industry

stakeholders and academics alike, for use as a base to explore further MiC opportunities for ASH.

2. Background

2.1. Modular Integrated Construction

MiC can be defined as the process of planning, design, manufacturing, fabrication and preassembling of various building elements, components and modules in an enclosed environment, often called factory production, before their final installation on site to support a rapid permanent structure [25,26]. It is also referred to as other terms such as offsite construction, offsite manufacturing (OSM), offsite production (OSP), offsite fabrication (OSF), modern methods of construction (MMC), prefabrication, industrialized construction, volumetric, non-volumetric preassembly, component subassembly and panelized assembly in different countries [27]. Figure 1 shows the literal meaning of each word in MiC as stated by Pan and Hon 2020 [28].

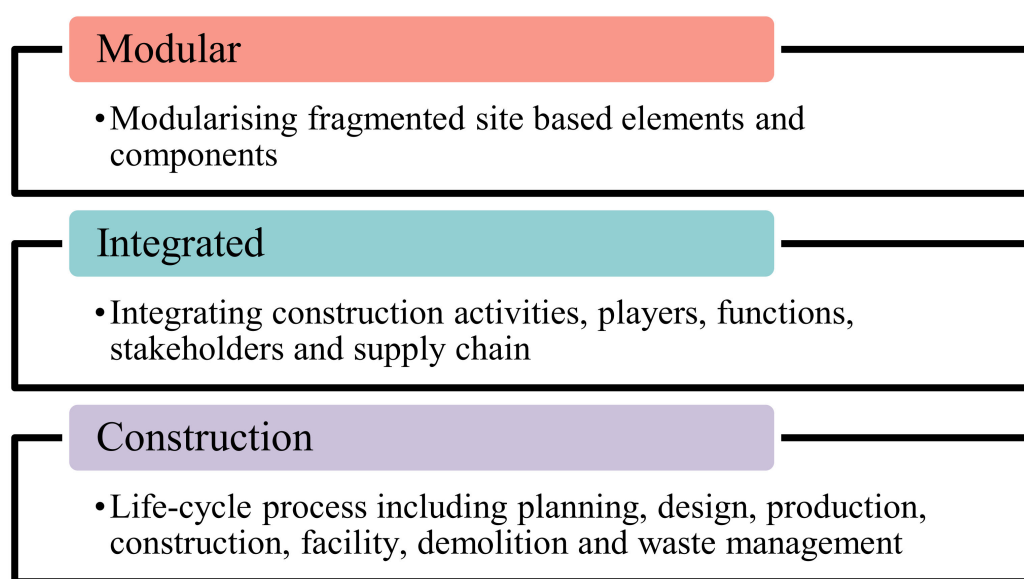


Figure 1. Breakdown of Modular Integrated Construction.

MiC came from the concept of modularity, which is to create pieces of a product in a secluded manner while still being configured or integrated to different systems utilizing similar engineering concepts. The process allows diverse configuration options for modules to achieve desired results [29]. MiC methods are derived from the theories of modularity and modularization, where modularity is defined as the disintegration of complex systems into smaller components that can interact based on specific standards and rules [30]. The simpler interface of a complex system makes modularity suitable for the construction industry as each element can be viewed in isolation and independently before integrating it into a complex building system. On the other hand, modularization is defined as the pre-making of a complex system involving large modules into smaller elements before transporting them to the site [31]. Figure 2 reflects the process of typical MiC method including all the steps governed throughout different stages of the construction.

Similar to Lego brick assembly, the installation process of MiC is a stack of different modules placed on top of each other to complete the structure. The rise of MiC has been seen in recent years due to the vast benefits it offers in comparison with traditional construction methods. Kamali and Hewage [32] mentioned the lifecycle benefits of MiC and Wuni and Shen [33] documented the critical success factors of MiC projects in the construction industry. MiC methods have been used in various types of building projects such as houses, hospitals, hotels, offices, retail outlets, universities and supermarkets [25,34,35]. Several researchers believed that MiC is the future of the construction industry due to the

vast benefits it possesses and mitigating the problems caused by the traditional methods of construction [36–38].

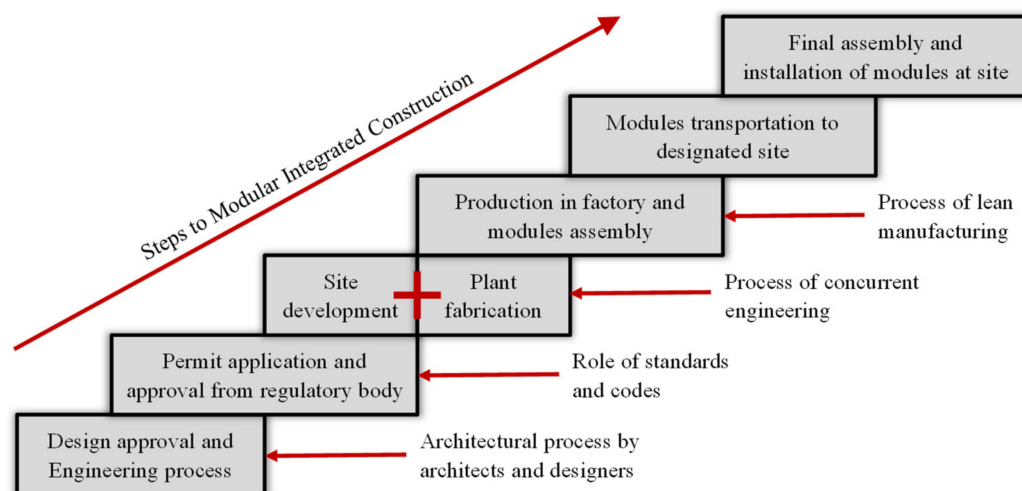


Figure 2. Steps of Modular Integrated Construction.

The design process of the MiC method follows an amalgamated methodology of Design for Manufacture (DfM) and Design for Assembly (DFA) theories. This approach eases the fabrication process to enhance the assembly process of modules generated within the timeline of the assigned schedule at a more rapid speed, lower cost, higher quality and with increased productivity. Meanwhile, the principles of concurrent engineering applied in MiC projects allow site development and plant fabrication at the same time, unlike stick-built construction methods [39]. The design of modules should comply with the local authorities' codes and standards as the MiC method does not have any specific standards [40]. Often, this stage requires the involvement of many stakeholders such as the client, contractor, supplier and fabricator. Collaboration, information and communication are the three most concrete pillars for achieving a successful MiC project. Note that MiC projects usually adopt steel frame, concrete or hybrid modules [41].

While the design process in MiC is a crucial stage, the offsite manufacturing, supply chain and logistics, and onsite assembly stages are also significant for a successful MiC project. The offsite manufacturing requires a factory production where bespoke modules or components are constructed [42]. This stage acts as a bridge between initial and final stages of MiC implementation. Although the success of this stage lies in effective collaboration and communication between project participants, suitable procurement strategies for materials, effective resource planning and scheduling and utilizing just-in-time methods for module production among others, there are certain risk factors that can affect this stage [43]. Dimensional conflicts between modules, defective design and information gaps, frequently changing orders from clients, inadequate inspection procedures, scheduling errors causing rework and low capabilities of manufacturers among other things, are some of the risk factors that hinder the factory production stage of the MiC method [44].

After the production of modules, delivery to the site is required. Although a straightforward process, it can be inundated with risks which are potentially impacting to successful logistics. Transportation restrictions in terms of size and weight, poor scheduling, inadequate marking and tagging of modules and defects due to damage/flexing/warping and manual handling of the modules, are some of the issues that have to be addressed for successfully accomplishing the logistics of delivering modules to site [45]. Finally, onsite assembly marks the end of MiC's stages in supply chain management. Critical factors at this stage include efficient path and layout planning of cranes, adequate buffer space for the modules and stability during module placements. As the site can be affected by weather disruptions, the just-in-time concept of module delivery is best suited to avoid unnecessary delays and risks in module settlement. Taking proactive measures against

risks and applying optimization techniques at each of these stages, can lead to successful MiC project results. Further, integrating recent digital technologies at each stage of MiC not only makes the process faster and smoother, but also enhances the sustainability aspects of it [46].

2.2. Affordable Sustainable Housing

The word “affordable” is subjective and can carry different meanings to different parties. Contrasting views on the definition of AH are documented in previous studies [7,47–50]. Among various measures taken to define affordability, income is one of the top measures hence AH can be determined by the expenditure to income ratio. Some previous research states that in terms of income, affordable housing should not exceed more than 30% of the inhabitant’s income. In addition, supply–demand hierarchy factors play a major role in defining affordable housing.

Amongst the different types of housing in the market, not many are affordable. Studies related to housing [7,47–50] have described the affordability in housing as a relationship between income and expenditure along with many other factors to consider. These factors include but are not limited to, finance cost structure, availability, occupation needs of relevant demographics, housing process distribution and government policies towards the requirements. Other than the financial affordability, the location and quality of a house should also be sufficient to be considered affordable housing [7]. While the idea of AH is to deliver houses to low- or moderate-income households, appropriate and cost-saving design and construction methods for AH have been dwindling, unable to meet the required upsurge in demand. That underpins the shortcomings inherent in the present processes of designing and constructing AH, and such a crisis is leaving stakeholders with little or no solutions. In light of such an AH emergency, the way in which AH is built should be transformed in a manner that makes it more financially practical as well as more environmentally friendly.

AH should be sustainable, as well as minimizing the living cost of residents. However, as Chan and Adabre [51] stated, “not all that is affordable can be counted as sustainable”. Therefore, bridging that gap to add a sustainability aspect to affordable housing is critical, since the building sector accounts for 40% of energy consumption and constitutes 30% of carbon emissions to the environment [52]. Although there are a wide range of studies focusing on affordable housing, the integration of sustainable innovative methods has been missing [13]. A utilization of sustainable materials and methods during design, planning and operational stages, in addition to green practices, constitutes sustainable housing. Not only can such a sustainability aspect enhance the wellbeing of the residents living in these houses, but it will also reduce the environmental impact [16]. In addition to delivering habitable spaces, ASH should also prioritize consideration of the socio-economic development benefits it produces. Scrutinizing affordable housing through the lens of sustainable innovation is essential to the design of resilient urban spaces and durable housing for people [53]. However, an empirical consideration of innovative and modern techniques has not been adequately studied for ASH. Deploying innovative methods of construction with affordability and sustainability in mind, is crucial for developing inclusive and cohesive sustainable communities [16].

One of the UN’s SDGs is to provide ASH to the entire relevant population that is in need of it, but at this stage achieving that target remains an aspiration [2]. Meanwhile, urbanization and the movement of people towards cities without a proper livable habitat, has resulted in the rise of slums or shanty houses in most developing countries [13]. As elucidated in a number of scholarly articles, the issue of slums remains a problem given the minimal development of strategies working towards achieving ASH [13]. Although continuous efforts regarding mandating and delivering ASH have been carried out by governments and relevant organizations, challenges remain.

The lack of a commonly accepted definition of ASH is fraught with many hurdles and is a contentious debate remains among stakeholders and in scholarly articles. It is

important to include sustainability measures based on innovation, economic, social and environmental among others into AH to deliver low cost, high quality and durable dwellings to people. Several criteria for success [24,51] and barriers [54,55] toward achieving ASH have been reported by researchers in the existing literature. Moghayedi et al. [13] identified various critical success factors (CSFs) of ASH and divided them into environmental, social, technical and economic subcategories. In a similar study, Adabre and Chan [24] highlighted 30 CSFs of the development of ASH and subdivided them into developer enabling CSFs, household demand enabling CSFs, mixed land use CSFs and land use planning CSFs. Adabre et al. [54] categorized 26 critical barriers in ASH allocating them under social, economic, institutional and environmental barriers. Other barriers reported in previous studies include lack of knowledge towards sustainability and innovation, insufficient design capabilities, construction methods and efficient materials among others [56–58]. A few studies argued that innovation in all spheres has the potential to upgrade the development of ASH [13]; however, limited studies have explored such methods and innovations.

On the other hand, the growing demand for sustainability principles and societal needs calls for innovative practices of housing construction. Although housing is stated as one of the primary requirements by the United Nations, the problem of low or negligible delivery of adequate affordable housing exists among developed and developing countries [2]. According to a report by the UN in 2017, around 1.6 billion people reside in inadequate houses in unhygienic micro-environments [59]. The approach of delivering better households coupled with low price, high quality, better productivity and environment friendliness should be considered by housing policies and authorities. Low-income housing is often perceived to reduce existing property values within their neighborhoods, due to traditional views prevalent in the market such as NIMBY principles (“not in my backyard”). Such factors contribute to a shortage of low-income housing schemes such as affordable housing. These factors make it imperative to study drivers for adopting MiC as a strategy for ASH upliftment.

2.3. Application of MiC in Affordable Sustainable Housing

A significant housing shortage is an issue in many regions, as the demand for shelter for a growing population around the world remains unfulfilled [60]. MiC methods can fulfill this requirement by taking significantly less construction time. The application of MiC in ASH has been explored in a few studies highlighting the benefits and merits that MiC can have on the upsurge of ASH in both developing and developed countries. Nanyam et al. [61] suggested utilizing manufacturing methods such as last planner, lean and six sigma with offsite methods to augment the process of ASH. Along with manufacturing, some techniques related to Industrial Revolution 4.0 in the construction industry could also benefit the pressing issue of quick ASH delivery. Building Information Modelling (BIM), visualization tools such as VR, 3D printing and other enabling technologies have changed the process of design, construction and operation. The application of these digital technologies in the process of MiC can not only hasten the provision of ASH, but also progresses towards a brighter more sustainable future, in accordance with the UN’s SDG goals of 2030.

Although MiC is considered to be the solution to such a housing crisis, its uptake is still low and lags behind in many countries due to an assortment of factors. However, following a few inactive years, a revolution in the MiC sector is rising due to the upsurge in digital technologies adopted in the Architecture, Engineering and Construction (AEC) field such as BIM and BIM-related visualization techniques which make the process of design and construction faster and easier to implement. As the construction industry is inundated with setbacks related to increasing its efficiency towards better quality and productivity, problems such as the sustainable nature of construction are increasingly scrutinized, since construction is one of the top industries responsible for a large contribution towards carbon emissions [62]. Although MiC is considered as one of the sustainable practices of

construction and is deemed as the perfect methodology for depleting the housing crisis, the application of MiC towards ASH is still underutilized.

MiC and other offsite construction methods are proven to be a sustainable option for delivering ASH. For instance, Australian Engineers declared a climate and biodiversity emergency for engineering teams to actively support the transition of their industry towards a low carbon and more sustainable future [63]. Improvements can be made to sustainability, strengthening environmental, social and economic parameters, and also reducing the use of non-renewable sources and facilitating the recycling of materials [21,64]. This aspect of MiC favors the Circular Economy movement whereas the modules, materials and other items can be recycled and reused [65,66]. Although MiC and other offsite construction techniques have been around during the last 30–40 years, the advancement and more recent integrative options of different cyber-physical systems with MiC can open a new wider range of automation and innovative ideas for ASH construction [67]. BIM, internet of things (IoT) and other cyber-physical systems (CPSs) integrated with MiC can be a significant boost towards affordable and sustainable dwellings.

3. Research Method

A three-way process has been adopted in this study, utilizing the TISM method, as well as some principles from some prior relevant studies. The first stage involved a comprehensive systematic literature review to identify drivers towards the adoption of MiC practices for ASH. Further, fifteen semi-structured interviews from domain experts were carried out to establish the connections between various variables. Finally, the TISM model was built to form an application framework for drivers, to understand the wider landscape. Figure 3 depicts the three-way methodology of this study.

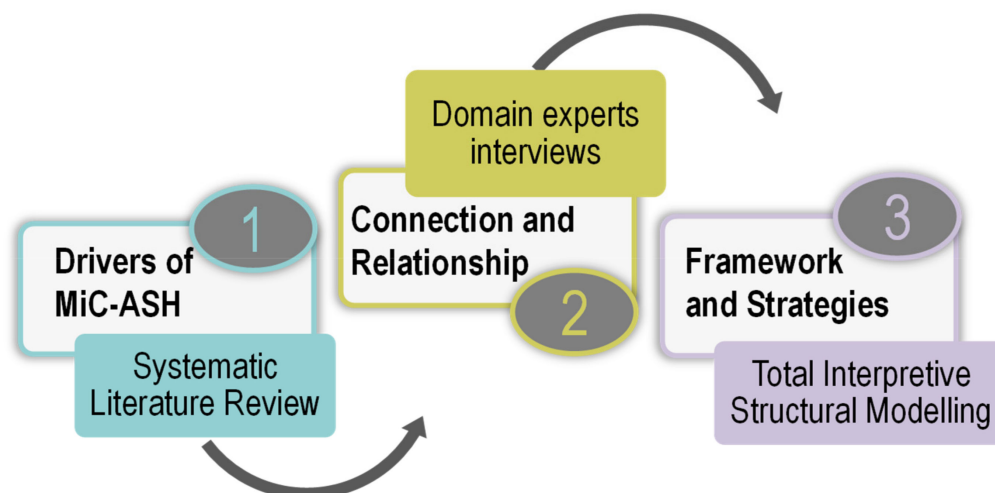


Figure 3. Three-way methodology of the proposed study.

3.1. Systematic Literature Review Procedure

A systematic literature review procedure is the first step in the TISM method, to review relevant articles for the proposed study. The article retrieval process was performed through the PRISMA method, which is a systematic data collection protocol involving four steps, namely identification, screening, eligibility and inclusion. This is a widely used data extraction process and is used by various researchers across the AEC field [68]. Figure 4 shows the steps of the PRISMA protocol for the article collection process.

3.1.1. Identification

To identify the relevant publications for the study, initially, keywords relevant to the study were found based on an unconstrained and unconstructed search. In addition to this, keywords used by previous studies in a similar domain were also considered. The Scopus database was used for the search as it is one of the authoritative search engines

and has a wide variety and landscape of publications in comparison to other sources (such as the Web of Sciences and Google Scholar) [69]. The keywords identified were divided into three domains viz.-MiC, drivers and ASH. For a more comprehensive search, similar nomenclature for each domain was also considered. In the MiC, other keywords such as “modular construction”, “prefabrication”, “prefabricated”, “offsite construction”, “offsite manufacturing”, “offsite production”, “modern method of construction”, “industrialized construction”, “industrialized building systems”, “systems building” and “prefabricated prefinished volumetric construction” were used. Similarly, for drivers, analogous keywords such as “benefits”, “advantages”, “enablers”, “merits” and “factors” were considered. Finally, for ASH, keywords such as “affordable housing” and “sustainable housing” were included to keep it more specific. The adequacy of these keywords was considered to be rigorously based on the previous studies in similar domains [24,70]. The keywords were then entered in the Scopus search engine using the TITLE-ABS-KEY procedure and a total number of 270 articles were retrieved to proceed to the next stage of screening.

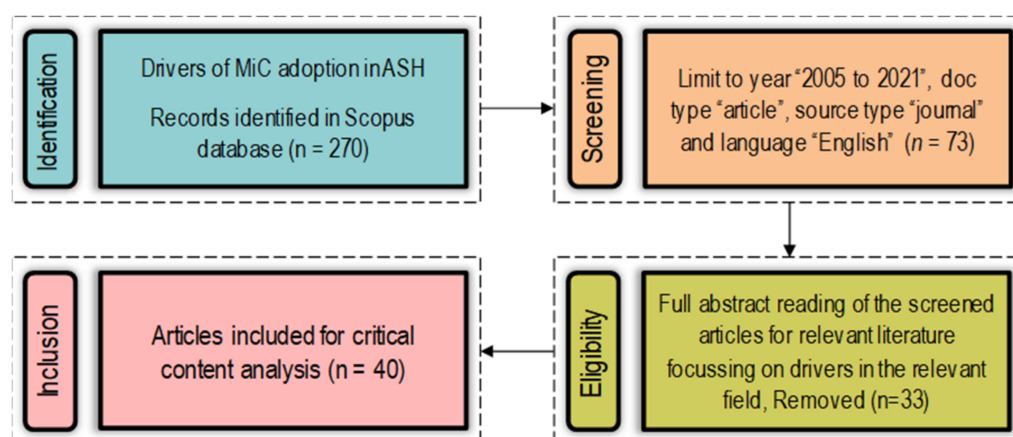


Figure 4. Steps of the PRISMA protocol for the article collection process. (Note: *n* represents number of articles).

3.1.2. Screening

The screening process was carried out in this step based on the following criteria: (1) Years of publications ranged from 2005 to present, as studies before that were deemed not relevant and thus out of scope, also the existing literature for the subject matter was scarce before the year 2005; (2) document type and source type were confined to articles and journals, as other document types and source types were not considered as peer-reviewed, thus articles and journals were deemed to provide the only authentic data set used for this study; and (3) language was restricted to English only. A total of 73 articles remained after this step.

3.1.3. Eligibility

In the eligibility phase, a full abstract reading of all the articles was performed, and some papers were filtered out based upon the following criteria: (1) Lack of focus on the subject matter; (2) either talking about ASH or MiC individually but not in an integrated manner; (3) related to other sectors such as manufacturing; and (4) only using ASH and/or MiC as keywords but not in a direct application towards our subject. A total of 33 articles were removed at this stage.

3.1.4. Inclusion

Ultimately, 40 articles pertaining to the drivers were selected and were included for the content analysis, at this step. All 40 of those articles were critically analyzed, and via synthesis eight consolidated driving factors were categorized from them: time, cost, quality, productivity, social, environmental, demand and policy.

3.2. Domain Experts Semi-Structured Interview

Following the analysis and categorization of drivers from the literature, semi-structured interviews were conducted from fifteen domain experts in the MiC or other OSC techniques. The interview covered questions broadly related to MiC such as drivers and barriers of MiC, risks in MiC, digital technology adoption in MiC, and how MiC adoption can be increased and future of MiC. The semi-structured interviews facilitate prompt and in-depth comprehension of the subject matter through expert experience and knowledge [71]. The participants for the interview were selected based on a purposeful sampling method which acknowledges the underlying information of a subject. The criteria for selection were as follows: (1) the participants must have extensive knowledge of MiC and other OSC techniques; and (2) the participants should have experience of the housing sector, especially public housing.

Fifteen interviewees had diverse backgrounds of architecture, civil engineering, surveying engineering and structure engineering. This ensured diverse opinions and expertise to comment towards the subject matter, thus delivering adequate interview-based information. Further, the varied positions of the interviewees within their organizations facilitated varied perspectives towards addressing any potential problems related to MiC implementation for ASH. The interviews were conducted online due to face-to-face pandemic restrictions. The interviews lasted for around one hour, and they were recorded, transcribed and analyzed for content insight. Throughout the rest of the paper, interviewees are labeled as P1–P15 (Participants 1–15).

3.3. Total Interpretive Structural Modelling (TISM) Method

In this study, TISM was adopted to construct a conceptual framework for the drivers of MiC adoption for ASH. TISM is an extended version of Interpretive Structural Modelling (ISM) which was introduced by Warfield [72]. As the name suggests, ISM is a modeling approach to understanding the relationship between various variables in a multifaceted problem based on the interpretations and judgments of the working groups involved [72,73].

Although ISM facilitates the recognition of relationships between different variables in a problem, it is not capable of elucidating the causal connections between them [74]. Therefore, TISM was developed as an extended version of ISM with a clear hierarchical structure of the variables along with evident interactions and interdependencies between them [74,75]. Drawing on concepts from system thinking [23] and graph theory [76], TISM uses digraphs to build the framework and map the interactions and links between the variables in the system. For understanding the multidimensional factors of MiC adoption in ASH, where the dynamics of the system rely on connections between the different factors, TISM delivers greater insights and implementation relations. Although a significant methodology is utilized in many fields, TISM has been implemented by AEC researchers in several domains such as “barriers of lean construction implementation [77]”, “challenges faced by the construction industry in COVID-19 era [78]” and “readiness of lean procurement methods [79]”. Figure 5 shows the steps in the TISM approach with the explanation of the steps in the context of the study in Section 4.3.

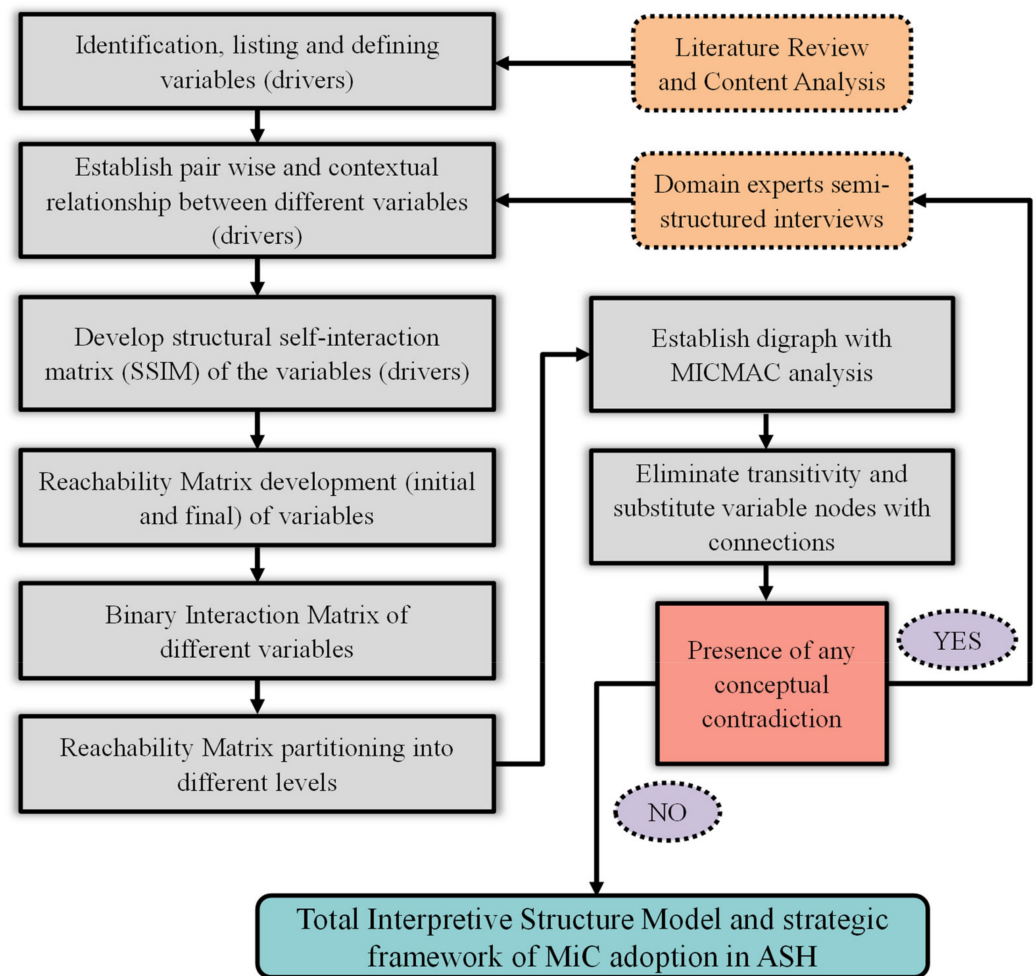


Figure 5. Steps in TISM approach.

4. Result Findings and Discussions

4.1. Analysis of Drivers towards the Adoption of MiC for ASH

Through the systematic literature review and content analysis of 40 articles related to drivers of MiC for ASH, 111 driving factors which are significant in the context of the study were abstracted. After the abstraction of the drivers, clustering was performed to group the drivers following the classifications from previous relevant studies [24,70]. The imperative classification of drivers was categorized into “Cost”, “Time”, “Productivity”, “Quality”, “Environmental”, “Social”, “Policy” and “Demand”. Each cluster is explained and discussed in the below sections to deliver and facilitate understanding in a deeper sense, and to illuminate a wider landscape of the literature around each of them. Figure 6 shows the list of drivers grouped under each cluster.

4.1.1. Cost Drivers

Traditionally, cost escalation is common in the construction industry [80]. Several reports argued that construction projects have cost overruns, with many projects executed up to 80% over budget [81]. One of the key drivers to implement MiC in ASH is cost-effectiveness, since the methodology of MiC is based on concurrent engineering principles which should reduce unnecessary cost escalation during the project stages. However, a few arguments suggest that some perplexity over actual costs in MiC projects remains, with mixed opinions and experiences that MiC increases or decreases cost over the entire lifecycle [20,21]. It is anticipated that although MiC has a higher initial cost, it may lead to whole-of-life cost savings. According to a recent report by McKinsey Global Institute, MiC reduces costs by up to 20% during the project implementation phases and can also deliver

lifecycles cost benefits [1]. Recent studies proclaim that MiC is a cost-effective solution, which is a significant driver in the successful implementation and widespread solution for ASH among both developing and developed countries around the world [65,80]. Reduction in costs related to capital, operations, rework, lifecycle, design, construction, labor and price of the product are driving forces to implement MiC for ASH [33,82–84]. Thus, the overall lower cost of utilizing MiC compared to using traditional construction methods for ASH is a significant driver.



Figure 6. List of drivers grouped in clusters.

4.1.2. Time Drivers

Since the supply of ASH is being delivered within the current context of huge demand, its construction time duration is a significant limiting factor, and thus quicker construction methods are required. In 2016 for instance, a report by McKinsey [81] declared that the construction industry was “ripe for disruption,” noting that 20% of large projects are typically delivered late, and 80% are delivered over budget. Housing authorities around the world are striving for faster provision of homes to their needy inhabitants amidst such a crisis. For instance, the current housing needs of Australia are estimated to be 1.3 million households, escalating further up to 1.7 million by 2025 [85]. To tackle this urgent issue of delivering low-cost, high-value ASH, MiC is the ideal construction technique to adopt [17]. Time management is always crucial for the success of construction projects,

since time delays and overruns are considered one of the serious plagues of the construction industry [20,86]. As such, MiC has been proven to be a time-saving construction method with up to a 70% reduced time in comparison to traditional construction techniques [87,88]. The concurrent engineering process utilized by the MiC method, is proven to lessen construction time. The time related driving factors for utilizing MiC for ASH are its quick construction period [83], lead time reduction [89], faster return on investment [90], less design and planning time [91], less weather disruptions [92], enhanced schedule implementation [93] and abridged timescale for the overall project [80] among many others. Si et al. [94] in their recent study advocated MiC as a just-in-time delivery method, and proposed a framework which reflects that MiC is a modern method that reduces the risk of any natural disruptions causing delays in the project. Further, Yao [95] reflected that time performance is the crucial factor for supporting MiC as the fast construction method recently used to construct an emergency pandemic hospital in Huoshenshan in China, therefore in addition to solving the usual time-bound issues for developers and other stakeholders, MiC is also a speedy construction process in case of emergencies.

4.1.3. Productivity Drivers

As per the Oxford Dictionary, productivity is defined as “effectiveness of productive effort measured in terms of rate of output per unit of input” [96]. Productivity in the construction industry is often measured by the effectiveness of labor, equipment, construction methods, site management and materials [97]. There is currently a shortage of skilled labor in the construction industry: according to a recent analysis by Statista 2020 [98] around 975,000 workers lost their job due to ramifications of the pandemic. In addition, a large number of workers and younger people are reluctant to pursue a career option in the physically exhausting construction industry [67]. This skills shortage issue calls for more efficient utilization of manufacturing and automation techniques in the construction industry. One fear among stakeholders in adopting more automation in the industry, is that it may result in increased loss of jobs; however, a recent analysis by the World Economic Forum stated that the inclusion of automation techniques will also create approximately 58 million jobs by the year 2025 [67]. Adopting more automation throughout the MiC industry may provide an opportunity for a new wider labor force to enter into this sector. Productivity is also a variable contingent upon the health and safety of workers, which can also be boosted by using MiC methods of construction. A McGraw Hill Smart Market report revealed that 44% of contractors think that MiC methods are a positive impact upon health and safety of workers [99]. ASH is heavily reliant on low-cost construction, and via optimized coupling of MiC techniques together with automation, each unit can be delivered and produced using less labor which makes ASH more palatable to the stakeholders. Some factors for further improving productivity in the construction industry include: improvements in technology adoption, better measurement of performance, clearer goal setting, more role clarity, better distribution of incentives, enhanced feedback and enhanced motivation [100]. The construction industry is often considered to be plagued with low productivity, and has been acknowledged as the least productive sector with only a 1% annual increase since the last two decades contrasted with the manufacturing industry [81]. The fragmented business model of conventional construction methods is one of the major reasons for such low productivity, as it follows a linear approach instead of concurrent or parallel engineering processes [101]. To improve such productivity issues, manufacturing-based business models and construction methods such as MiC and other offsite construction techniques were advocated in previous research studies and in industry reports [81,96]. As compared to conventional construction methods, MiC and other offsite construction techniques have proven to positively impact productivity [99]. Some of the driving productivity factors for adopting MiC for ASH or for general construction projects, include enhanced site operations, better integrity and durability of buildings, more predictability in performance, reduced defects, better project customization and customer-driven standards [83,91,102–105]. The application of robotics and automation systems is capable

of producing higher output with a better product at a lower unit cost [67]. In light of the growth in demand, there is anticipated to be a dire need to implement automation techniques in the modular construction market, with the global market increasing to be approximately 109 billion dollars by the year 2025 [106]. The manufacturing factory-based environment utilized in the MiC process supports better coordination, streamlining of repeating tasks and enhanced levels of automation that are capable of cutting the schedules of the project by 30–50% and costs by 20–25%, thus enhancing the overall productivity of the project [67]. Although higher initial costs and capital expenditures are required for such an automation process, which hampers stakeholder interest, research has suggested that producing high volumes of modular units, as in the case of the deliveries of ASH to residents, can also provide increased motivation for stakeholders to utilize more automation techniques in the construction industry. Therefore, it is imperative to consider productivity as one of the significant drivers to boost MiC use for ASH.

4.1.4. Quality Drivers

Previous studies showed that the quality of ASH is of ordinary standards and at times unsuitable for inhabitants and that affordable and low-cost housings are delivered by government and public organizations with less focus on quality output [107]. Given the relatively low profit margins, the interest of private developers towards ASH is low [47]. In addition, the social stigma that the presence of low-cost housings in the neighborhood decreases the property value is also prevalent. Moreover, it is reported in previous studies that low-cost housing tends to be performing below clients' satisfaction [108]. MiC and other off-site construction techniques offer better quality products in areas, such as sustainability and low waste generation. Zhang et al. [20] highlighted that enhanced quality can be achieved in MiC modules as the modules are regulated, checked and tested in a controlled factory environment before the assembly process. Use of MiC can lead to superior consistency, reduced defects and damage, better project quality control, upgraded life cycle performance and enhanced durability, leading to an enhanced quality of end product [20]. The utilization of MiC in ASH will not only deliver high-quality consistent modules, but also produce repetitive modules on a large scale to solve the crisis of affordability in the housing in most of the countries. Thus, the justification of implementing MiC in ASH relies heavily on quality driving factors.

4.1.5. Environmental Drivers

The construction industry is a large contributor to climate change around the world [109]. Energy-efficient methods in the construction industry are in urgent need to successfully comply with United Nations sustainable development goals SDGs. Regarding the environmental and sustainable features of the MiC method, the well-implemented MiC project proves to be sustainable in aspects, such as reducing the overall time of delivery by following concurrent engineering principles [110], reducing water footprint [111] and toxic emission of gases [112]. Adoption of MiC reduces the emission of a greenhouse by 32 kg/m² [112] and reduces the waste up to 52%, as seen in the Hong Kong construction industry [113]. While many studies reported the environmental and sustainability benefits of utilizing MiC over traditional construction methods, the application of MiC to ASH is still uncommon [17]. The environmental advantage is an important factor that can drive the adoption of MiC in ASH [17]. Improved environmental sustainability, low waste and pollution, increased building performance, decreased site and weather disruptions, low carbon emission and escalated building comfort are driving factors of implementing MiC in ASH. The environmental impact of modular homes is reported to be lower compared to conventional homes, resulting in overall lifecycle benefits [114,115]. Therefore, environmental benefits are a significant driver to adopt MiC practices in ASH.

4.1.6. Social Drivers

The International Association for Impact Assessment (IAIA) [116] defines the social performance or social impact of a project or technology as projected and non-projected consequences caused by the planned interventions and any positive or negative social changes implored by those interventions. In the construction industry, the social sustainability of a project is a result of the smooth engagement of clients, employees, community and other stakeholders to envision the requirements of current and future communities. Although most of the construction projects are profit-related rather than envisioning social impacts, ASH requires significant profits in terms of social integration of the communities and populations [53,117]. The substantial way to measure the social factors as a driving force in utilizing MiC in ASH is by knowing the capacity of various key performance indicators (KPIs) related to it. Pan et al. [100] in their industry report cited health, safety, satisfaction and social impact as the relevant KPIs to quantify social drivers of MiC. The report suggested the quantifiable benefits of MiC in terms of measuring KPIs are better than conventional construction methods. Pan et al. [118] in their other report found that MiC enhances health and safety prospects, accelerated project delivery, improved the overall industry image and decreases the disturbances to the community. Referring to huge benefits in achieving social harmony, the social drivers are prophesized for using MiC in ASH.

4.1.7. Policy Drivers

The development and implementation of vigorous policies towards applying MiC methods in ASH is a significant driving factor. The robust frameworks and policies made by policymakers towards increasing the use of MiC and other offsite construction methods in ASH are seen in many developed and developing countries around the world [100]. The government's role in providing policies, guidelines, bylaws, support, incentives, schemes and regulations is considered to be a huge boost and encouragement towards the utilization of MiC in ASH [96]. Globally, governments are backing modern methods of construction, particularly MiC and other offsite construction methods to address the pressing challenges of housing affordability in diverse ways [66]. Not only could tribulations over housing affordability be addressed to a large extent by applying MiC methods, but also endemic skill shortages in the construction industry are pushing modern methods of construction quicker than ever [67]. Countries such as Sweden, Japan and Poland are pioneers in adopting MiC methods to meet their housing demands. The weather limitations and demographical restrictions of these countries are also considered by the policies of the government. For instance, in Sweden, the government has targeted a goal of 250,000 modular and sustainable homes delivery by 2020 to resolve the rising crisis of housing [119]; however, the goal is disturbed due to the pandemic, and the delivery is anticipated to be delayed by a year. Similarly, government schemes in developed countries such as the USA, UK, Australia and Canada are pushing the streamlined process of housing delivery amidst rising concerns of the housing shortage [96]. In the USA, along with realizing modular construction as an innovative approach for housing demands, the individual capital cities of different states are taking their measure to curb the crisis in the housing sector. The 70\$ million projects in New York City aim to deliver ASH using MiC methods as planned by New York city's Department of Housing preservation and development [120]. In a directive by the UK government, the mobilization of affordable housing delivery must use MiC and other off-site construction methods by at least 25% [121]. On contrary, the Canadian government cited the factors of labor shortage and low-skilled workers that boost the utilization of MiC methods for ASH delivery [122]. In Australia, the grappling situation of a housing shortage which is projected to rise by 1.7 million by 2025 calls for strict measures by the government and related organizations [122]. However, the Australian government expects that gaining traction in the housing space will only be achievable by escalating the manufacturing industry and making them the trailblazers to lead the way. Regarding this, the Cooperative Research Centre (CRC) of Australia has developed an industry-led research initiative known as Building 4.0 CRC which has an individual theme of housing

and urban design focusing on affordability domains. In New Zealand, a government-led real estate development body named Kiwi Build is formulated in 2018 aiming to deliver 100,000 ASH using MiC methods by 2028 [123]. In Asian countries, the government is playing a key role in the upliftment of offsite construction technologies in China, Hong Kong, Japan, South Korea and Malaysia among others. For instance, in Singapore, the government launched an Industry Transformation Map (ITM) in 2017 which underpins the usage of digital technologies and offsite construction techniques in the infrastructure areas with a focus on housing [124]. Similarly, in Hong Kong, a Construction Innovation and Technology Fund is granted by the government to promote MiC and other digital technologies of construction in the housing development [118]. Meanwhile, in developing countries such as India, the government is underway to construct 10 million modular homes by 2022 using offsite construction methods to eradicate housing shortages in the country [122]. Often, MiC and other offsite techniques are considered to be the last resort; however, the government needs to implement it in the initial planning and business cases. Thus, robust policies and frameworks are the key drivers in adopting MiC for ASH.

4.1.8. Demand Drivers

The escalating population in the world necessitates the delivery of housing solutions on a mass scale because many developed and developing countries around the world are facing a scarcity of housing [12,53]. On the other hand, the construction industry is anticipated to be one of the largest contributors to carbon emission, thus sustainable solutions are needed to provide housing to people [62]. Integrating these two aspects, the supply of ASH concomitant with MiC practices provides solutions to this pressing concern. The unprecedented advantages of MiC are not only in domains of sustainability, but also it is a time-saving and cost-effective remedy. However, demand also depends upon demographical and geographical characteristics of countries as well in adopting quick solutions such as MiC and other offsite construction methods. For instance, Nordic and Scandinavian countries such as Sweden, Norway, Denmark and Poland could rely on MiC solutions for housing purposes due to the long duration of cold weather around the year which does not suit extended hours in conventional construction methods. The controlled factory environment of MiC deliverance reduces weather disruptions, thus making MiC for ASH an in-demand process [44]. Asian countries, such as China and Japan have constraints on land availability, which makes MiC an effective solution to deliver ASH in the form of sustainable high-rise housing buildings. Oceanic regions such as Australia and New Zealand are lagging in achieving climatic goals as prescribed in the Paris Climate agreement 2050 which have been exacerbated due to concerns around bushfires as well. In this respect, MiC for providing mass scale ASH is relevant and should be accelerated in these countries too. Citing demands from social, economic and sustainability perspectives, MiC and other offsite construction methods are solutions for the countries to provide ASH.

4.2. TISM Model and MICMAC Analysis for Drivers of MiC Adoption in ASH

Seven steps in TISM model and MICMAC analysis are outlined below.

Step 1—The first step in developing the TISM is to identify, list and define variables of the problem. In this study, the drivers for MiC adoption in ASH were identified following the systematic literature review process, as outlined and described in Section 4.1. Due to the large number of the drivers, they were divided into eight clusters namely cost, time, productivity, quality, environmental, social, policy and demand. The categorization of drivers into different clusters was adopted from similar studies such as Blismas and Wakefield [38] and Wong et al. [90].

Step 2—The second step is to establish a pairwise and contextual relationship between different variables to develop a structural self-interaction matrix (SSIM) of the variables. The pair-wise relation is also known as the adjacency matrix, which was developed analyzing the fifteen semi-structured interviews. The paired matrix between the eight drivers was developed initially followed by a cross exploration of drivers to identify the influence

over each other. After analyzing the occurrences of each pairing of drivers from the interview transcriptions, a SSIM was developed as shown in Table 1. In this table, the contextual relationship between the different drivers to form the adjacency matrix were denoted by letters V, A, X and O: V denotes that driver “i” leads or influences driver “j”; A denotes that driver “j” leads or influences driver “i”; X denotes that both drivers “i” and “j” lead or influence each other; and O denotes that both drivers “i” and “j” do not lead or influence each other. Sushil [74] suggested that for each “i,j” pair in the matrix, the nature of the relationship can be observed; and based on yes or no reactions, the compilation of interactions and transitive links between drivers can be developed.

Table 1. SSIM of the drivers.

i \ j	DR-8	DR-7	DR-6	DR-5	DR-4	DR-3	DR-2	DR-1
DR-1	V	A	X	V	A	X	A	X
DR-2	V	O	X	O	A	X	X	-
DR-3	V	V	A	A	X	X	-	-
DR-4	A	A	A	V	X	-	-	-
DR-5	V	A	O	X	-	-	-	-
DR-6	X	X	X	-	-	-	-	-
DR-7	X	X	-	-	-	-	-	-
DR-8	X	-	-	-	-	-	-	-

As can be seen in Table 1, mixed nature of interactions between drivers are developed following the discussion process. The effects of each driver on each other are also shown in the matrix diagram in Figure 7.

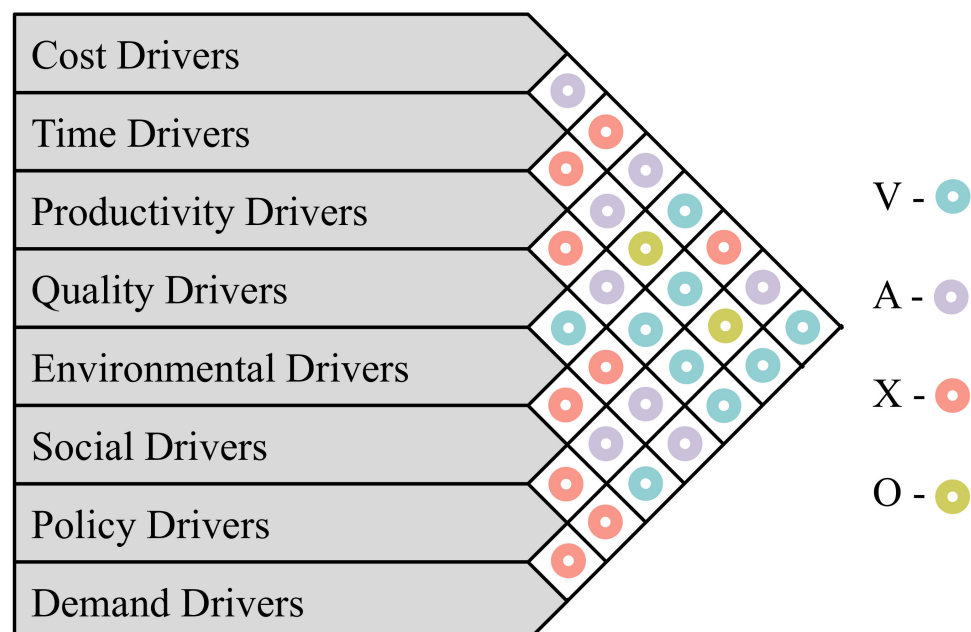


Figure 7. SSIM depiction in matrix diagram.

Step 3—The third step is to develop the Reachability Matrix (RM), which differs from adjacency matrix as the latter only defines the direct relationship or context between the drivers, while the former highlights both the direct and indirect relationship between each driver. Implementing the Interpretive Logic Knowledge Base, the initial RM was developed between the drivers to form a paired comparison between them. Based on

the AM developed, two levels of initial and final RM were developed. The initial RM level followed the rules of binary values 0 and 1 to replace the V, A, X and O letters. The interpretation was demonstrated as follows based on interpretations from Sushil [74]:

- For every V in the cell, the entry (i,j) becomes 1, and entry (j,i) becomes 0.
- For every A in the cell, the entry (i,j) becomes 0, and entry (j,i) becomes 1.
- For every X in the cell, the entry (i,j) becomes 1, and entry (j,i) also becomes 1.
- For every O in the cell, both the entries (i,j) and (j,i) become 0.

Further, to check the transitivity rules, the power iteration analysis is necessary to develop the final RM. As the initial RM only reflects the direct relationships between the variables, it is necessary to perform a transitivity check to explore the indirect relationships as well [125]. The transitivity check (*) maintains the consistency among the driver relations and was conducted utilizing Boolean operation of self-multiplication to reach a stable state [22], for instance, if driver DR-1 affects DR-2 and DR-2 affects DR-3, then DR-1 also affects DR-3 indirectly. The expression used for generating the final RM is as follows as shown in Equation (1):

$$R_f = R_i^k + R_i^{k+1}, K > 1 \quad (1)$$

where R_f denotes final RM and R_i denotes initial RM [126]. The final RM values are reflected in Table 2. Driving power of a driver is a number representing other drivers that affects the outcome. Dependence power of a driver is a number representing other drivers that is affected by it. It is evident from Table 2 that there are few transitive links between drivers which allows maintaining the model consistency throughout the iteration process.

Table 2. RM for the drivers.

Drivers	DR-1	DR-2	DR-3	DR-4	DR-5	DR-6	DR-7	DR-8	Driving Power
DR-1	1	0	1	0	1	1	0	1	5
DR-2	1	1	1	0	1	1	0	1	6
DR-3	1	1	1	1 *	0	0	1	1	6
DR-4	1	1	1	1	1	0	1	0	6
DR-5	0	1 *	1	0	1	0	0	1 *	4
DR-6	1	1	1	1	0	1	1 *	1	7
DR-7	1	0	0	1 *	1	1	1	1	6
DR-8	0	1	0	1	0	0	1	1	4
Dependency Power	6	6	6	5	5	4	5	7	-

Note: (*) denotes the transitivity relation check.

Step 4—The fourth step is to develop a level partitioning matrix based on a hierarchy structure. The partitioning of levels to form a hierarchy structure is based on forming reachability set, antecedent set and intersection set. The reachability set of a driver includes all the drivers that it may reach, the antecedent set of a driver includes all the drivers that reach it, and the intersection set of a driver includes all the common drivers from reachability and antecedent sets.

After deriving the reachability set and antecedent set for each driver from the RM, the intersection set was developed. The determination of levels for each driver is based on the comparison of the reachability set and the intersection set. The similar nature of drivers in both sets was placed accordingly in levels based on different iterations. The repetition of iterations was calculated consecutively, which led to a four-level hierarchy from level 1 to level 4. Similar approaches were used in other studies based on principles of TISM [78,125]. Table 3 shows the iterative level partitioning matrix based on the hierarchy structure.

As shown in Table 3, level 1 includes two drivers, namely DR-5 (Environmental) and DR-8 (Demand), meanwhile only one, DR-6 (Social) is in level 4. All the others are either in level 2 or 3 as seen in Table 3. The lower-level drivers would be above in the

hierarchy, implying that they will be affected by others lower in the hierarchy structure. On the contrary, the higher-level driver is the lowest in the hierarchy table and has a great influence or affect others above them. Others situated in the middle levels lead to the drivers above them in the hierarchy structure and lead by drivers on the bottom in the hierarchy structure.

Table 3. Level partitioning matrix based on hierarchy structure.

Drivers	Reachability Set	Antecedent Set	Intersection Set	Level
DR-1	1, 3, 5, 6, 8	1, 2, 3, 4, 6, 7	1, 3, 6	2
DR-2	1, 2, 3, 5, 6, 8	2, 3, 4, 5, 6, 8	2, 3, 5, 6, 8	2
DR-3	1, 2, 3, 4, 7, 8	1, 2, 3, 4, 5, 6	1, 2, 3, 4	3
DR-4	1, 2, 3, 4, 5, 7	3, 4, 6, 7, 8	3, 4, 7	2
DR-5	2, 3, 5, 8	1, 2, 4, 5, 7	2, 5	1
DR-6	1, 2, 3, 4, 6, 7, 8	1, 2, 6, 7	1, 2, 6, 7	4
DR-7	1, 4, 5, 6, 7, 8	3, 4, 6, 7, 8	4, 6, 7, 8	3
DR-8	2, 4, 7, 8	1, 2, 3, 5, 6, 7, 8	2, 7, 8	1

Step 5—The fifth step is to perform MICMAC analysis. The hierarchy levels in Table 3 facilitate the MICMAC analysis. Matrice d’ Impacts Croises-Multiplication Appliqué a Classement (MICMAC) analysis is used to examine the distribution of impacts for a variable by identifying their driving and dependence power. The driving and dependence power of each driver was calculated and discussed in Table 2. MICMAC analysis is utilized to place the drivers of MiC-ASH into four different categories of dependent (weak driving power and strong dependence power), driving or independent (strong driving power and weak dependence power), autonomous (weak driving power and weak dependence power) and linkage (strong driving power and strong dependence power). This analysis is applied to examine the interactions of drivers based on the capabilities towards their driving or dependence powers as explained in Step 4. Figure 8 shows the MiC-ASH drivers in four quadrants. These quadrants are set based on the scale centric method as directed by Sushil [75] and Warfield [127]. All the drivers’ location in Figure 8 are based on their driving and dependence powers in the RM and is facilitated by cross-impact matrix multiplication.

It is evident in Figure 8 that five drivers are in the linkage quadrant which have strong driving and dependence power: DR-1 (Cost), DR-2 (Time), DR-3 (Productivity), DR-4 (Quality) and DR-7 (Policy). There are two drivers in the dependent quadrant which have weak driving and strong dependence power: DR-5 (Environmental) and DR-8 (Demand). Only one driver is located in the driving or independent quadrant with strong driving and weak dependence power, which is DR-6 (Social). There are no drivers situated in the autonomous quadrant.

Steps 6 and 7—The final step is to develop the transitive links between different drivers and build a TISM model. Based on the earlier steps of developing RM and MICMAC analysis, the transitive links are developed to explain the relationship between connected drivers [74]. Applying the theoretical underpinnings of the system thinking approach and interpretive logic knowledge base, the TISM model was developed. Table 4 shows the transitive links between each driver wherever applicable to reflect the interactions between them as presented in Figure 9. The TISM model in Figure 9 reflects the landscape of eight drivers of MiC-ASH adoption synergy. From the TISM model, it is evident that DR-6 (Social) is the most significant driver with the highest driving power and lowest dependency power. All the other drivers are dependent on social drivers as can be seen from the transitive links in Table 4 and Figure 9. For instance, the policies developed by the government organizations are significantly related to the social-driven impacts and thus require a clear understanding of social aspects [24]. Further, interviewee P1 said “Issues such as mindset of the different stakeholders, especially end user is critical to

enabling success and I believe unless the industry is forced to change, nothing substantial will happen". Social drivers also influence the drivers in the linkage quadrant which are situated in level 2 and level 3. However, DR-3 (Productivity) and DR-7 (Policy) are in level 3 and influence DR-2 (Time), DR-4 (Quality) and DR-1 (Cost) by transitive links such as enhanced schedule, government incentives and controlled work scenarios. The drivers in level 1 namely DR-5 (Environmental) and DR-8 (Demand) also have a remarkable effect on MiC-ASH adoption, but they heavily rely on the success of the other lower-level drivers. For instance, as Figure 9 suggests, the shortage of ASH which is a social factor is responsible for demand growth, and policies such as incentives, schemes, or regulations also influence demand growth. Many interviewees (P2, P5, P6, P10, P12, P14, P15) said that incorporating circular economy principles into MiC would make their utilization more widespread and would also escalate the environmental drivers for MiC. Interviewee P7 said that "I think off the back of success for MiC for ASH, we will definitely see a huge rise in the circular economy". Brissi et al. [17] in their recent study suggested social factors to be the impactful decision maker, when talking about the demand, it depends upon customer attitude, perceptions and budget requirements. In a similar study, Festus et al. [53] reflected the social factors such as capital, inclusion and cohesion as the significant factors for demand growth. Further, interviewee P5 emphasized that "there's a shortage of houses doesn't matter where we go, and the shortage is purely because of the cost, the time or the logistics that ultimately affects demand, we need to solve these problems before we can have an impact and I don't think we're doing that yet".

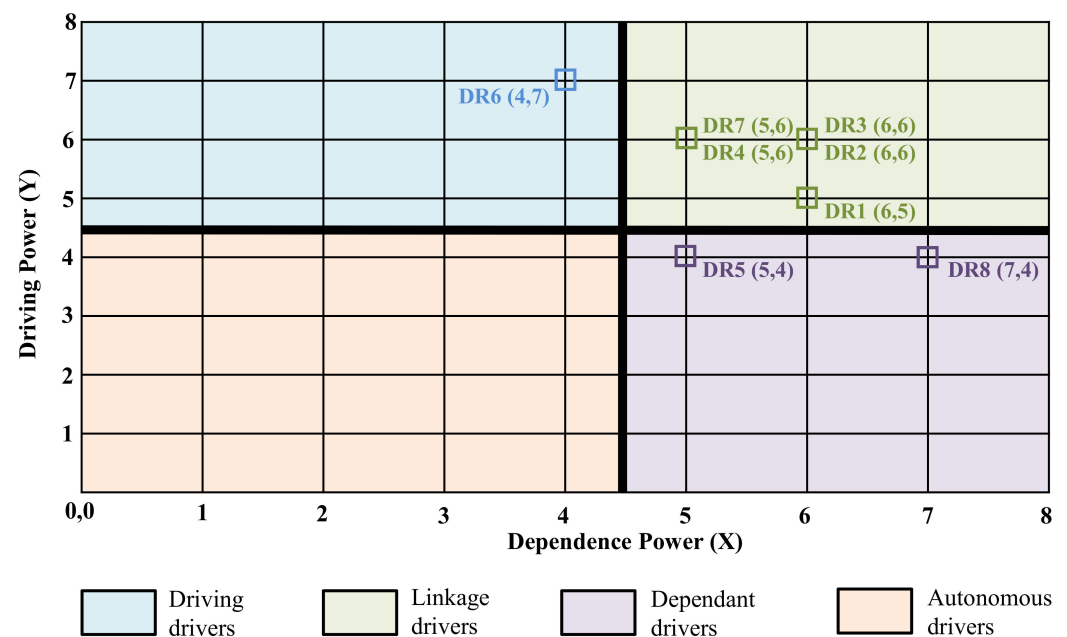
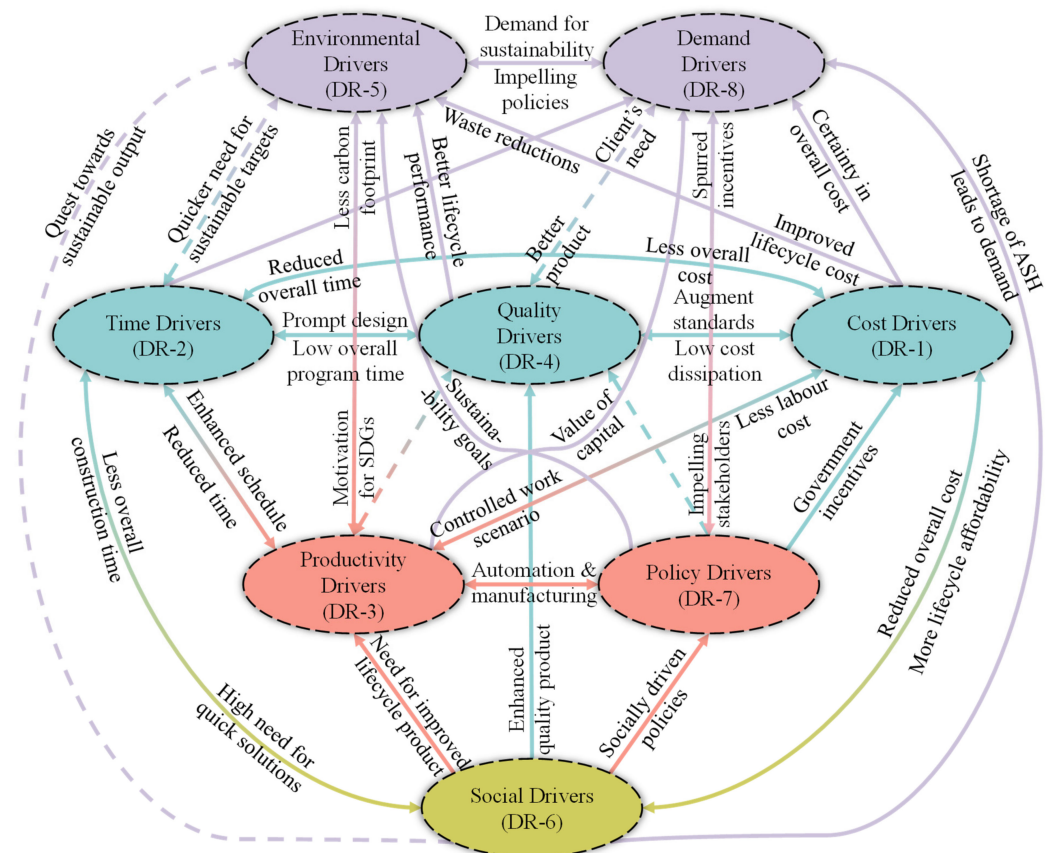


Figure 8. MICMAC analysis of the drivers of MiC-ASH.

Therefore, the level-1 drivers DR-5 (Environment) and DR-8 (Demand) have absolute dependency on the championing of other drivers at lower levels such as Time, Quality and Cost followed by Productivity and Policy. Thus, the prioritization of level-2 and level-3 drivers is significant for the performance of level-1 drivers. In some cases, the two drivers are not directly linked, however affecting each other. For instance, DR-4 (Quality) connects with DR-8 (Demand) on factors such as client's need and better product expectations. In conclusion, the TISM model presents a pool of drivers and their links to each other which are noteworthy and substantial in terms of identifying the importance of each driver when adopting MiC for ASH.

Table 4. Drivers' transitive links with each other based on TISM.

Drivers	DR-1	DR-2	DR-3	DR-4	DR-5	DR-6	DR-7	DR-8
DR-1	-	Reduced overall time	Controlled work scenario	Augmented standards	Waste reductions	More lifecycle affordability	-	Certainty in overall cost
DR-2	Less overall cost	-	Enhanced schedule	Prompt design	Quicker need for sustainable goals	High need for quick solutions	-	-
DR-3	Less labor cost	Reduced time	-	-	Less carbon footprint	-	Call for manufacturing policies	Value of capital
DR-4	Low-cost dissipation	Low overall program time	-	-	Better lifecycle performance	-	-	Client's demand
DR-5	Improved lifecycle cost		Motivation for SDGs	-	-	-	-	Demand for sustainability
DR-6	Reduced overall cost	Less overall construction time	Need for improved lifecycle product	Enhanced quality product	The quest towards sustainable output	-	Socially driven policies	Shortage of ASH leads to demand
DR-7	Government incentives	-	Promoting automation	-	Sustainability goals	-	-	Spurred incentives
DR-8	-	-	-	Better product	Impelling policies	-	Impelling stakeholders	-

**Figure 9.** TISM model of the drivers of MiC-ASH.

4.3. The Strategic Framework of Boosting MiC Adoption in ASH

Along with providing the TISM model and MICMAC analysis of the identified drivers, further strategies for boosting these drivers for MiC-ASH are identified and presented for future recommendations. Figure 10 provides a list of drivers along with key stakeholders to be involved for strategic boosting of the factors. The studies in the existing literature identified the drivers, but lack in providing the connections between them, the importance of each, and further strategic framework to enhance them [20]. The strategies and championing stakeholders in Figure 10 are extracted from the 40 studies critically analyzed in this paper, along with semi-structured interview results [2,98,116]. The stakeholders who can uplift the cost drivers are banking authorities/investors, research centers, government policies and academicians (P1, P4, P5, P11). Most of the clients and developers are profit-driven and often lack motivation towards ASH delivery (P4); this calls for encouraging public–private partnerships and streamlining the process of loans and incentives from the banking authorities (P1, P11). It was pointed out by interviewee P5 that “Banks need to get onboard and understand a new process is a good thing and not a risk they shouldn’t fund”. Moreover, the cost–benefit aspect of MiC has not been promoted to public, and there is a lack of research in this sustainable construction method [21]. Therefore, it would be beneficial if research institutes/centers, and academicians can deliver effective projects which highlight the cost value and return on investment scenarios of MiC (P1, P4).

Regarding time drivers of MiC-ASH adoption, the quintessential factors are the innovative manufacturing process (P2), utilization of disruptive technologies (P7), clarity in collaborative thinking (P14), and commitments from academic institutions (P3, P15). Many developed countries are still lacking in their manufacturing capabilities in the construction industry [82]. For instance, Australia relies heavily on countries such as China and Singapore for their modular construction deliveries due to a lack of domestic manufacturing capabilities, this takes a considerable amount of time and heavy cost due to taxes incurred [118]. Therefore, manufacturing competency is essential to boosting MiC to be able to deliver low-cost and time-efficient MiC solutions. Interviewee P2 stated that the success of manufacturing MiC modules lies in “Manufacturing techniques, ability to manufacture complex geometries, time for manufacturing, cost of initial model, long time negotiation before starting the manufacturing and selecting the appropriate company”. Other than that, the interoperability issues among different stakeholders make the project lengthy and thus collaborating issues occur, as was pointed out by all of the architect interviewees (P1, P4, P5, P6, P8, P11, P14). In this regard, a few recent advances in blockchain technology have proved to be non-bias information-sharing practices [128]. However, still in proof-of-concept forms, blockchain is a technology counters the transparency issues in information sharing [129].

The productivity drivers can be boosted by the efforts of architects, designers, engineers and manufacturers among other relevant stakeholders. Moreover, the smooth supply chain management and superior training of the labor working offsite and onsite need to be heightened (P6, P9). Interviewee P9 stated that to enhance productivity “Just in time approach is very critical for supply chain of modular construction and can easily avoid the risk associated with the lack of space usage and lack of space required to store raw materials as well as ready modules on the site”. The clear directives and knowledge sharing between clients/developers and architects/designers ascertain the success of the project by having a progressive design and engineering process of MiC modules for ASH [38,89]. The process of MiC is still new to the labor working offsite and onsite, training and learning programs should be encouraged to obtain maximum output and productivity from the workers (P11, P15). Technologies, such as learning through a gaming environment are an effective way to train and assess the workers’ knowledge and upskill their capabilities (P11). Ali and Soto [130] developed a game engine platform for better coordination and connection between different teams in a modular construction project. In addition to this, productivity also relies on smooth supply chain management in regards to MiC-ASH

to balance supply–demand arrangement [131]. Thus, a continuous effort from relevant stakeholders and processes in the MiC method will solidify the productivity drivers.

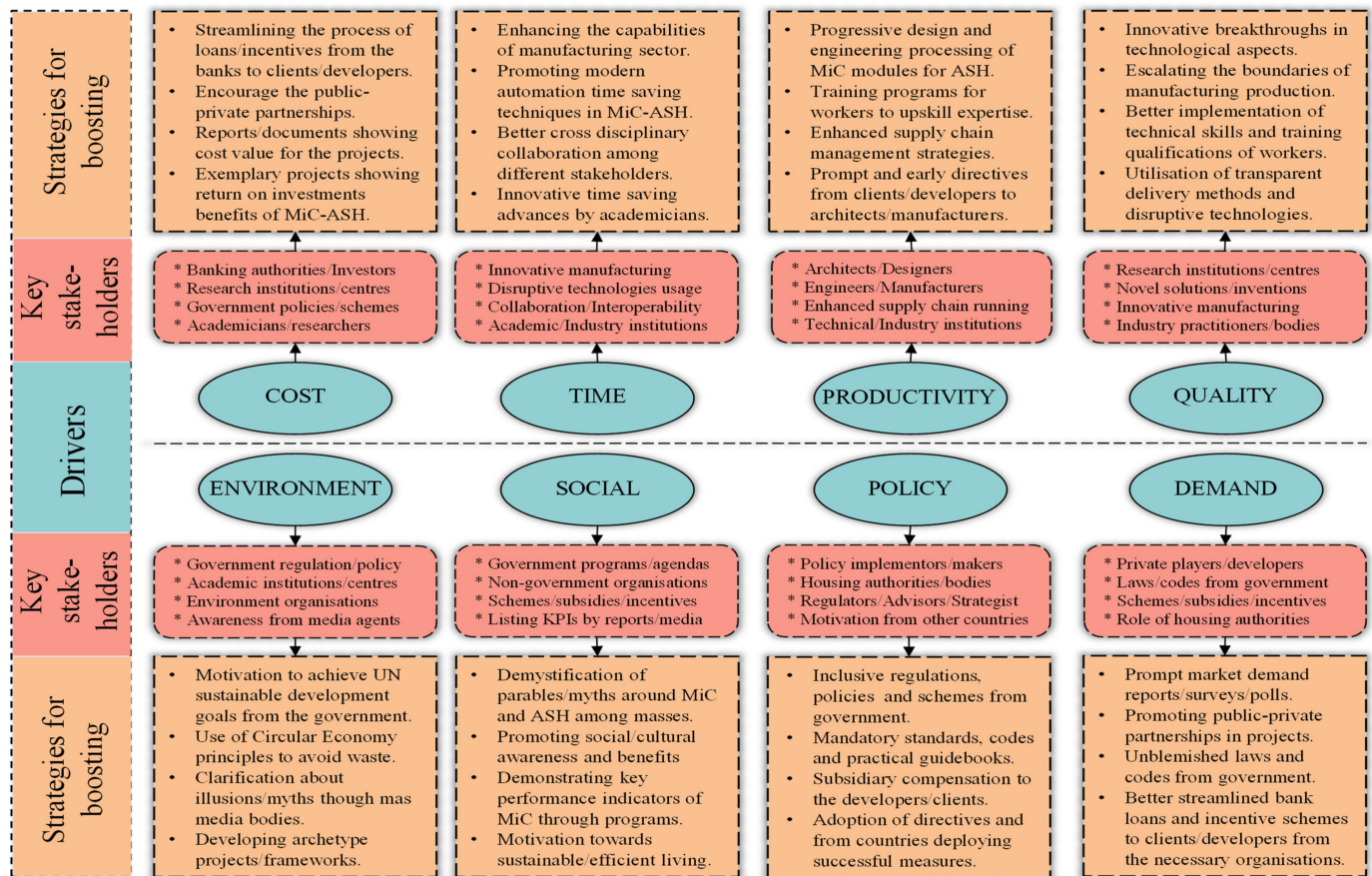


Figure 10. Strategic framework for boosting MiC-ASH integrity towards better adoption.

The quality of MiC is superior in comparison to conventional construction methods as the modules are created in a controlled factory environment [39]. Interviewee P6 believed that “In MiC, builders can work in the controlled and safe space with all the prerequisites of tools and equipment at their very disposal that leads to better form of built asset structures and also superior standard of quality”. However, insufficient capabilities of manufacturing processes, lack of automation techniques to streamline the workflow and lack of research in this domain often portray a similar image of MiC in comparison to conventional construction methods. To push the boosting of quality drivers, innovative breakthroughs in technological aspects and escalating the boundaries of manufacturing production are required [96]. Application of robotics in the production environment and deploying automation techniques in the factory will upgrade the quality of modules [67]. Additionally, after delivering modules to the site, a smooth assembly process is vital to maintain the quality of the product (P6, P7). Therefore, better implementation of technical skills and training qualifications of workers is required.

The role of environmental organizations, government regulations, academic institutions and awareness from media is significant for boosting the environmental drivers of MiC-ASH. Pertaining to the motivation of achieving UN sustainable development goals by the governments around the world, the adoption of MiC is crucial to deliver the burgeoning demand of ASH owing to the sustainable nature of the MiC method. Similarly, the potential of applying circular economy principles in MiC makes it a prodigious preference for ASH (P5, P6, P12, P14). A recent market report [65] quantifies the benefits of MiC when utilizing principles of circular economy which allows the “3R’s”, namely reduce, reuse and recycle, to effectively apply to the MiC method. Furthermore, academic institutions/centers need

to develop archetype projects and frameworks clarifying the myths and illusions around the sustainable benefits of MiC (P3, P10, P15).

Social drivers are the most critical component for MiC adoption in ASH. The stakeholders for boosting the social drivers are government programs and agendas, non-government organizations and raising awareness from the media among others (P1, P5, P7, P9, P11). The customer often has perception issues and has difficulty in ascertaining the value of the product and reluctance towards innovation and changes [17]. These parables or myths can be demystified by the government via promoting social and cultural awareness around the benefits of MiC for ASH. The role of non-government organizations is to motivate public towards sustainable and efficient aspects of MiC. Promotion of social capital schemes, social cohesion and inclusion parameters through government programs makes it easier for people to realize the fruitful advantages of MiC [53]. The demonstration of key performance indicators of MiC for ASH through market reports and academic research will also stimulate the process of MiC adoption in ASH delivery for public.

The stakeholders that are responsible to promote the policy drivers are policy makers, implementors, housing authorities, advisors and regulators. There is a lack of specific codes and standards in many countries regarding the MiC which impedes the process (P1, P4, P5, P8). There should be inclusive regulations, policies and schemes from respective governments to improve MiC management [101]. Client and developers often lack intent in producing ASH due to fewer profit margins, therefore subsidiary compensations along with encouraging public–private partnership directives should be laid out. Although a few regions such as Sweden, Poland, Hong Kong and Singapore have developed comprehensive guidelines and regulations for MiC adoption, their application is still suboptimal due to other factors such as enticements from the government and housing authorities [100].

Likewise, the understanding of the MiC process remains unclear to architects, manufacturers and construction managers (P1, P7, P11). In this regard, funding pilot projects and industry reports from the government would enhance the knowledge and process of MiC to relevant stakeholders. For instance, a recent report by the American Institute of Architects funded by the National Institute of Building Sciences provided a guide to architects for design of modular construction [132]. Similar efforts are required by the government bodies to promote the policy drivers of MiC-ASH adoption in their regions.

The demand for ASH has arisen in recent times among many developed and developing countries. The key stakeholders who are responsible for boosting the demand drivers are private developers, public–private partnerships, favorable laws and regulations from governments and the role of housing authorities [53]. The facilitation of demand drivers can be accelerated by performing demand surveys and polls among the people to explore their attitude and awareness about ASH and promoting the adoption (P3, P10, P15). For instance, in a recent study, Brissi et al. [17] highlighted the factors to consider when carrying out related polls or surveys. These factors include market demand, market trends, market maturity, targeted markets, market conditions, market size and cyclical changes, market forces, market analysis, demand gap and demand orientation. Moreover, interviewee P10 stated that “if marketing doesn’t work, then the product doesn’t work”. Other than that, as the demand would be fulfilled by the mixed efforts of private and public stakeholders, better agendas for public–private partnerships should be laid out, and private developers should be motivated by giving incentives and schemes from the government organizations. In addition, market reports can be facilitated by housing authorities to obtain knowledge of short-term and long-time demands in ASH [133].

5. Conclusions

Rising housing shortages around the world is a serious issue among many countries, and the ability of delivering ASH is currently being impeded by various factors. Alongside that phenomenon, the construction industry remains a slow adopter of modern methods of construction that could be more cost-effective and efficient. In recent years, there have been significant developments in offsite construction (OSC) techniques, especially modular

integrated construction (MiC) which is the complete form of OSC. Although MiC is utilized in many construction projects types, its benefits are not being leveraged in the sector of ASH. However, the literature suggests that MiC could be the solution to many of the problems of ASH, owing to MiC's speed, cost, sustainability and quality performance. Therefore, this study adopts a combined method of systematic literature review, semi-structured interviews and the Total Interpretive Structure Modelling (TISM) to study the drivers for MiC adoption in ASH. The 111 drivers extracted from the existing literature were grouped under eight clusters, including cost, time, productivity, quality, environmental, social, policy and demand. A TISM model for eight drivers was then developed with four levels of hierarchy containing linkage, driving, depending and autonomous drivers. The structural self-interaction matrix, reachability matrix and MICMAC analysis were used to assist the development of a TISM model. The analysis suggests that social drivers are the most significant driver, followed by productivity and policy drivers. To concretize the TISM model, a strategic framework of boosting the MiC adoption in ASH is provided to show the key champions and strategies to elevate the process of MiC adoption in ASH. The proposed framework fills the gap in the existing literature, namely the lack of knowledge about the connections between drivers of MiC adoption in ASH, the importance of such, and a further strategic framework to enhance adoption [20]. The pool of drivers presents a wider landscape towards MiC-ASH synergy assisting the relevant stakeholders. Moreover, the theoretical and practical contributions of the study are elaborated to cement the findings.

This study has various theoretical and practical contributions that can benefit relevant stakeholders for the wide adoption of MiC-ASH synergy. Theoretical innovations and contributions include: (1) an all-inclusive review of drivers of MiC-ASH has been conducted; (2) the study is the first study aiming to provide MiC-ASH integration possibilities; (3) an extended classification of 111 drivers into eight clusters is being used to develop a better understanding and comprehensiveness of the drivers of MiC-ASH from the literature study; (4) the study develops a transparent application framework using the TISM model to present a landscape of interactions between different drivers in the MiC-ASH amalgamation; (5) this study is the first research to utilize the TISM model approach to reflect the driving and depending drivers of the MiC-ASH; (6) this study presents an extensive pool of drivers for MiC-ASH adoption from the backdrop of further empirical studies on this topic; and finally; (7) this study presents a strategic framework for boosting MiC adoption in ASH.

Practical contributions of this study are: (1) the list of domains relevant to the MiC-ASH adoption along with specific driving factors are provided, which can provide a basis to inform relevant stakeholders about specific drivers; (2) the TISM model presents the opportunity for further investigations towards empirical research on the topic of rankings and hierarchies of drivers; (3) the details and dependencies of each driver will empower housing authorities, government bodies, managerial agencies and private players to prioritize resource allocations more optimally towards each driver; and finally, (4) this study lays the foundation for policy makers to implement appropriate laws and policies to promote specific drivers towards achieving wider adoption of ASH in their countries. Moreover, deploying modern methods of construction such as MiC with ASH is significant for the development of inclusive and cohesive communities in both developed and developing countries.

There are a few limitations of the study, firstly the validity of the TISM model will be further improved once more empirical information can be included. In future studies, survey will be conducted via wider relevant stakeholders. In addition, further analysis, such as fuzzy and sensitivity analysis, shall be conducted to further examine the relationship between the drivers.

Author Contributions: Conceptualization, A.K., R.Y., T.L., H.G. and E.O.; methodology, A.K.; formal analysis, A.K.; writing—original draft preparation, A.K.; writing—review and editing, R.Y., T.L., H.G. and E.O.; supervision, R.Y., T.L., H.G. and E.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with human research ethics, and approved by the Griffith University Human Research Ethics Committee (GU Ref No: 2021/556 and date of approval 29 July 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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