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Review

DfMA for a Better Industrialised Building System

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Abstract: To improve the performance of the construction industry, innovative methods were introduced to make them better. Industrialised building systems (IBS) and prefabrication construction are the popular methods used and studied. However, these methods are still unable to meet the demands of the stakeholders. Design for manufacturing and assembly (DfMA) is a design principle that is seen as capable of improving the situation. The uptake of DfMA in the construction industry needs to be analysed to obtain a better picture of the existing condition of the method and its manner of implementation it going forward, but there are still too few studies performed on this topic. This paper gathers relevant articles from the previous studies on DfMA. With the available data, the main benefits, hindrance factors, and enabling factors for DfMA uptake in the construction industry were identified in this study. The authors also identified the research trend among the research themes and the benefits of building information modelling (BIM) integration with DfMA. By synthesising the information from previous studies, a conceptual framework was developed. Knowledge gaps and future potential research topics are also discussed in this paper, forming a simple research framework for future effort guidance. With a suitable strategy and guidelines, the application of DfMA could improve the performance of the construction industry in Malaysia and other places with similar construction environments and approaches.

Keywords: DfMA; prefabricated construction; IBS; modern method construction; BIM

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1. Introduction

The construction industry is an important sector that not only directly contributes to a nation's economic growth but also indirectly through its connection to the growth of other industries [1]. The construction industry also has a high impact on a nation's environmental and social attributes. To a certain extent, the construction industry also influences the political profile [2].

"Traditional" is a word that characterises the construction industry, which has seen little evolution until recently [3]. Compared to other sectors, the construction industry, which is highly fragmented with a complicated process, a dynamic business environment, and a multi-stakeholder approach, is lagging in adopting innovation [4,5]. The cast-in-situ technique has been used in construction forever. Though the technique has survived for so long, so have the issues that come with its manual operation, non-standard method, fragmentation, and discontinuity. Typical construction methods still widely use falsework, wet trades, and scaffolding, and create lots of waste [6]. These issues reflect poorly on the environmental, economic, and social impact due to resource wastage and time overrun [7,8]. Productivity of construction, which is directly impacted by the productivity of labourers, often results in delays and wastage [9]. The productivity of the construction industry is declining while the manufacturing sector continues to increase its productivity [10].

To increase the construction industry's performance, prefabrication was introduced. Prefabrication construction is a part of the industrialised building system (IBS) [11], which includes producing building components in a controlled environment off-site or on-site to be assembled later on-site [12]. The potential of IBS in increasing the construction industry performance has been mentioned in several studies [13,14]. Based on case studies, IBS could help in reducing the time, increasing the quality, and reducing the dependency on unskilled labour [15,16]. However, the industry is still unable to tap the full potential of IBS where projects that already apply IBS still have issues with time and cost overrun and dependency on unskilled labour [17]. The lack of communication and cooperation [17–19] together with lack of knowledge and experience [20] among major stakeholders are the main issues.

Several researchers have described design for manufacture and assembly (DfMA) as a concept that could turn the IBS practice into a more efficient practice [21–23], such as in the manufacturing sector. Application of the DfMA principles would promote a design process that optimises manufacturing and assembly functions, which also leads to cost and time savings. Such a process would also have a high impact on product quality and customer satisfaction [22]. Adoption of DfMA could make construction viewed as an industrialised activity with increased productivity and predictability [21].

Prefabrication construction through DfMA has shown high potential in improving the construction industry productivity and reducing the cost of labour [23,24]. Modern prefabrication and off-site construction are currently producing complete or incomplete modules depending on the project requirements [25]. Building components could be produced like the production of cars [26].

Even though the application of DfMA is not necessarily digitalised, the usage of some technologies, such as building information modelling (BIM), could help to make it more productive, similar to how other processes are made more productive through digitalization [27–29]. By using BIM, the design work and design check could be completed in less time [30]. BIM also makes the transition from the design phase to the manufacturing phase and assembly phase simple [31,32]. Integrating BIM would enhance the efficacy of DfMA.

Though there are several reviews related to DfMA studies, few are of the same theme as this current study. The article by Gao et al. [33] looked at the perspective of the construction industry in implementing the DfMA concept or principles, which are (1) a holistic design process, (2) the evaluation of the efficiency of manufacturing and assembly, and (3) DfMA as a tool of technology in the prefabrication model. The review paper by Lu et al. [34] explored the principles of DfMA and other principles that can be integrated with DfMA to make the process more beneficial, as well as in-depth comparisons of the benefits of DfMA to other concepts that have been integrated into construction practice, such as lean construction and value management. Hyun et al. [20] conducted a review on the off-site construction design process with a consideration of DfMA. However, they did not discuss the application factors of DfMA. Review articles by Musa et al. [2] and Jin et al. [35] discussed the application of sustainable industrialised building systems and off-site construction, respectively. Both articles discussed the technology for prefabrication but neither review discussed integrating DfMA in the process. These studies did not look at the strategies or integrate the factors that influence the application of DfMA in the construction industry.

Despite the benefits of DfMA, its adoption in the construction industry is still relatively low and research linking DfMA to the construction industry is still limited [23,35]. There are too few data to influence the construction industry's players to adopt the principle. In a way, this hinders the construction industry from taking full advantage of DfMA. The objective of this study was to analyse the fragmented factors mentioned in previous studies that can influence the application of DfMA in the IBS project and the construction industry. From there, we developed a conceptual framework for DfMA application in the IBS project and the construction industry. It is hoped that this work can contribute to optimising the construction industry's performance and add to the body of knowledge in this particular area of study.

2. Description of DfMA Principles

According to Gao et al. [23], evaluating and improving product design for manufacturing and assembly by providing input on manufacturing during the design process can be implemented through the DfMA method of analysis. DfMA is the combination of design for manufacture (DfM) and design for assembly (DfA). Where DfM focuses on minimising part counts, DfA focuses on making attachment simpler. Both are based on basic rules, past data, or simulation, with cost and time reduction along the way [23,26,36,37]. As shown in Figure 1, DfMA can be perceived as a systematic procedure that, when applied as part of the design phase, would add value to the construction and production process. Evaluation of a design for its assembly efficiency with minimal components, parts, and materials that need to be handled on-site is another way to look at DfMA.

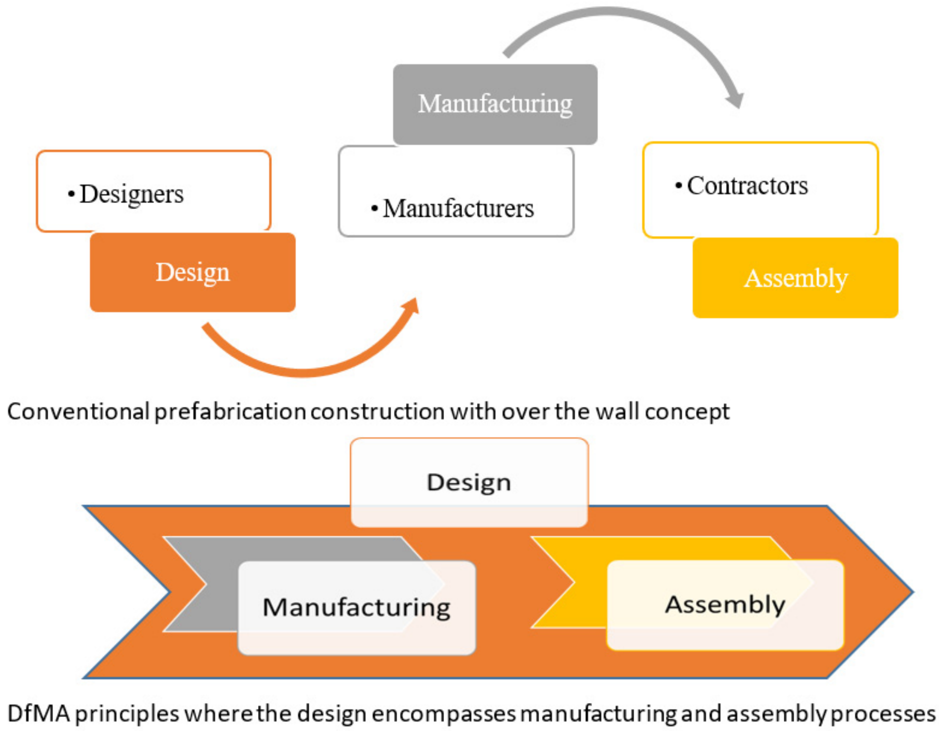

Figure 1. Simplified DfMA principles.

Another side of DfMA that is often referred to is prefabrication, to the extent that some equate DfMA with prefabrication, where construction work is completed off-site as much as possible [23]. Another definition of DfMA according to Mesa et al. [36] is simply a principle that improves design for manufacturing, assembly, and cost, where the main product function remains intact.

In a paper by Tik et al. [37], the Royal Institute of British Architects (RIBA) defines DfMA in construction as an approach that facilitates greater off-site manufacturing and minimises on-site construction. The following are levels of off-site DfMA categorised by RIBA: (1) component manufacturing, (2) sub-assembly, (3) non-volumetric preassembly, (4) volumetric preassembly, and (5) modular building.

In the same paper, it is stated that the Singapore Building and Construction Authority (BCA) defines DfMA as where construction is designed and detailed for a substantial portion of work to be performed off-site in a controlled manufacturing environment. DfMA is a new approach that, by planning more works off-site, ensures that the manpower and time needed to construct buildings are reduced, while ensuring work sites are safe, conducive, and have a minimal impact on the surrounding living environment. DfMA is promoted in the Singapore construction industry as a way to improve productivity in a traditionally manpower-intensive industry.

DfMA Recognition

According to Tan et al. [38], several countries have either introduced the DfMA guide or emphasised DfMA's importance in construction. Such countries are the United Kingdom, Singapore, and Hong Kong governments. Other than that, two industry giants have indicated DfMA as the future of construction.

Typically, in the building design and construction process, the designer might not be able to consider all possibilities of the design solution and miss the chance to implement what should be worth having. Information from other parties is usually not there during early-stage design, which relies on the designer's knowledge and experience and may be lacking in terms of assemblies and on-site operation. DfMA as an evaluation model could help in this area [33].

The core aim of DfMA is to help designers optimise prefabricated building design and improve its one-time success rate utilising and integrating professional knowledge and information from other stages into the design stage. So, the DfMA principle should be applied at an early stage of prefabricated building design as much as possible [39].

3. Methods

Literature reviews in research form the basis of knowledge to be studied. By analysing and synthesising data from previous studies, we can improve our understanding of the knowledge under our studies [40]. This study is based on the evaluation of literature from electronic databases of Web of Science (WoS) and Scopus. These two databases are known to be reference points for academic literature reviews due to their large collection and are often seen as having a higher academic contribution [41].

After reviewing the relevant articles on DfMA application in the construction industry, several topics are investigated. The topics are: (1) the pattern of studies on DfMA in the construction industry, (2) the benefits of DfMA in the construction industry, (3) the hindrance factors on DfMA uptake in the construction industry, and (4) the enabling factors for DfMA application in the construction industry. Based on the findings from the four topics above, the trends and knowledge gap are then discussed. Science mapping is used only for the intention of depicturing the pattern of previous studies that are referred to in this current study since this work is not intended to be a bibliometric study. Figure 2 shows the overall layout of the research methodology.

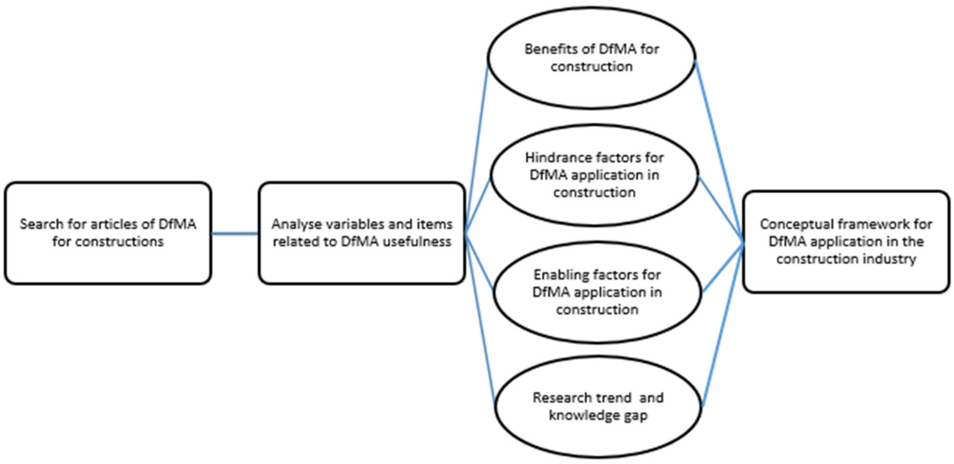

Figure 2. Overall methodology.

4. Results

4.1. Pattern of DfMA for Construction Studies

Based on the scientometric review by Derbe et al. [41], this study adopted the science mapping approach using VOSviewer software (1.6.17 version, Nees Jan van Eck and Ludo Waltman, Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands) to look at the trends of research conducted under this study's topic. As a reference, several papers have used this software for studies in the field of construction and review articles [41]. The analysis using this software uses the data extracted from the related articles referred to for the current study. Using the software data mining ability, networks are visualised using science mapping that shows the linkage of research keywords and countries involved. From this network map, the evolution of a research topic can be traced and the main players can be identified.

Analysis of research keywords or phrases can reflect the researched area in a certain research domain [42]. The network of the keywords show interrelations of a certain research area [42]. In this study, the network of research keywords co-occurrence is generated based on documents referred to in this study. It can be seen here that the main keyword in this area of study is "prefabrication". Prefabrication has been studied earlier compared to DfMA, which is a relatively new research area. The bigger node size also shows that there are more studies carried out on a particular subject [42].

Figure 3 shows that referred documents on prefabrication started, on average, in mid-2019 based on the colour of the node. Documents in 2020 look at off-site construction and DfMA. In 2021, the referred documents looked at policies, engineering design, feature recognition, and sustainable development, which are also linked to prefabrication and DfMA. This shows a certain advancement of technology involved in prefabrication to have optimization in construction through DfMA. Documents related to BIM also started in 2019 but do not seem to be connected to the other keywords.

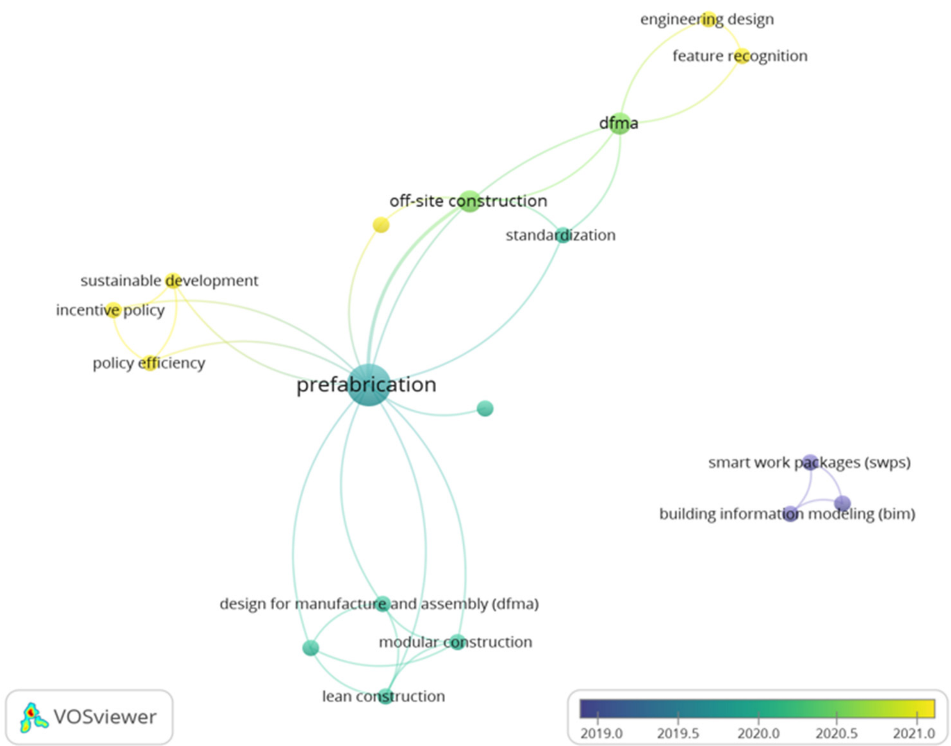

Figure 3. Science mapping of research keywords of referred papers.

Figure 4 shows the main countries involved in the research on DfMA in construction. Referred documents on this topic started around 2018 and England is the main contributor.

As can be seen on the map, most countries that contributed to this research are connected. The research also involves countries from almost all continents. There are still few countries involved in this research topic, which is also relatively still new. This could indicate the relevance of the topic for current research on construction optimization.

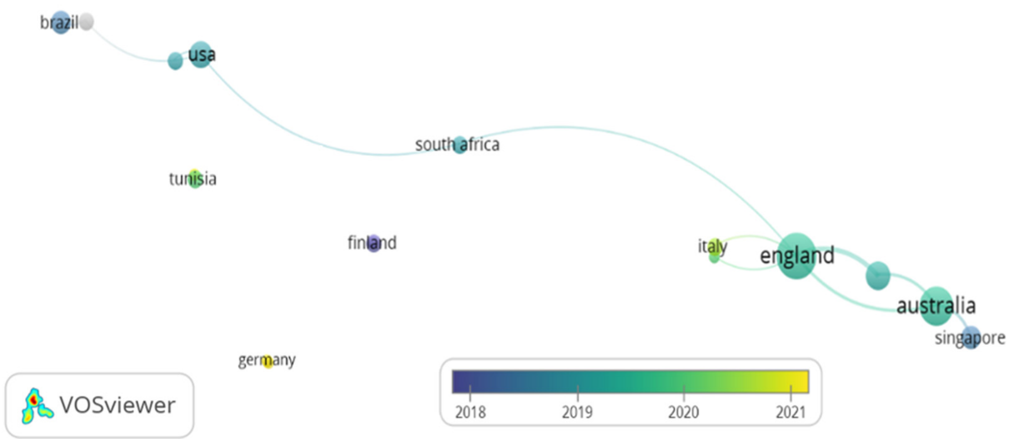

Figure 4. Countries involved in DfMA for construction research.

4.2. Benefit of DfMA in the Construction Industry

The typical benefits of DfMA in the construction industry would be reduced time, reduced cost, higher quality, and increased reliability. Reduction in time and cost is due to the reduction of waste and labour time. Waste minimization and lower labour cost occur because DfMA design principles help to ease the overall manufacturing and assembly process since it is already pre-considered in the module or part design [21].

With waste minimization and controlled working conditions, DfMA module design and prefabrication design promote sustainable, safe, and reliable construction [22]. The benefit of DfMA that was rarely discussed is the ability to point out and fix inefficient procedures and promote continuous improvement in a design [43]. Removing fragmentation and improving collaboration are other benefits that the construction industry could use [26].

In discussing the benefits of DfMA, there could be confusion about the benefits of prefabrication. DfMA is a design principle that optimises manufacturing and assembly activities. Prefabrication construction is a process performed on-site or off-site, used to produce the construction itself. The benefits shown in Table 1 are the benefits of the DfMA design principle and the benefits shown in Table 2 are the benefits of using prefabrication in construction. While the benefits of using prefabrication and off-site construction would be beneficial for a specific project, the benefits of using DfMA principles could be beneficial in the long run since they could be replicated in future projects.

The benefits of prefabrication and DfMA may look similar since both aim for the same objective. DfMA could be seen as a tool to enhance the full potential of prefabrication.

4.3. The Hindrance Factor for DfMA Application in the Construction Industry

The application of innovative concepts has its challenges. DfMA in construction is an innovative concept taken from the manufacturing sector to be adopted in the construction industry. This adoption is an effort to optimise the efficiency of the construction industry [37]. However, the benefits are not enough to convince the industry to widely implement the concept. There are challenges and hindrance factors that need to be overcome. Table 3 shows the hindrance factor or the challenges in adopting DfMA in the construction industry.

Table 1. The benefits of DfMA in construction.

DfMA Benefits for Construction Industry	Specific Benefits	Authors
Shorter construction period	Speed	Banks et al. [21]
	Reduced production time, shorter construction period	Trinder [26], Tik et al. [37]
	Faster time-to-market	Gao et al. [33]
	A drop-in assembly time	Wasim et al. [43]
	Reduction in manufacturing cycle time	Ferreira et al. [44]
Lower cost of construction	Lower cost, reducing the cost, cost saving, construction cost reduction	Banks et al. [21], Basarir and Cem Altun [45], Trinder [26], Tik et al. [37], Gao et al. [33], Wasim et al. [43]
	Enhance cost-efficiency	Chen and Lu [22]
	Decrease in parts cost	Ferreira et al. [44]
	Reduced labour on-site	Tik et al. [37]
A safer and healthier workplace	Improved safety, improved health and safety	Banks et al. [21], Trinder [26], Tik et al. [37]
	Safety enhances high-worth career	Tik et al. [37]
Higher quality in construction product	Higher quality, increasing the quality, improved quality, improvement in quality	Basarir and Cem Altun [45], Chen and Lu [22], Trinder [26], Tik et al. [37], Gao et al. [33], Banks et al. [21]
	Reduction in defects	Wasim et al. [43]
Sustainable construction	Sustainability	Banks et al. [21]
	Reduced waste, reduced construction wastage	Chen and Lu [22], Trinder [26], Tik et al. [37], Wasim et al. [43]
	Less dust and noise pollution	Tik et al. [37]
Improve design and construction reliability	Reliability, increasing the reliability, improvement in reliability	Banks et al. [21], Basarir and Cem Altun [45], Gao et al. [33]
	Reduced failures	Ferreira et al. [44]
	Allows a designer to enhance the buildability of construction products through early-stage design consideration	Gbadamosi et al. [46]
	Predict manufacturability outcomes while designing	Favi et al. [47]
	Improved the aesthetic performance	Chen and Lu [22]
	Saved interior building space	Chen and Lu [22]
	Assist designers in the selection of a variety of alternate materials for building elements, identification of design features that make the manufacturing process unfeasible or too costly	Wasim et al. [43], Favi et al. [47]
Increase productivity	Reducing number of parts, Reduction in parts count, Minimum number of parts	Basarir and Cem Altun [45], Gao et al. [33], Wasim et al. [43]
	Increase productivity, Productivity improvement	Trinder [26], Tik et al. [37]
	Remove team fragmentation and improve collaboration	Trinder [26]
	Tackle material shortages	Wasim et al. [43]

Table 2. Benefits of prefabrication and off-site construction.

Benefits in General	Benefits in Details	Authors
Better construction quality	Better building quality and high-quality control, better quality, enhanced quality, increasing on-site construction quality and efficiency, quality control, high-quality product	Musa et al. [2], Lu et al. [34], Yuan et al. [39], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]
Better efficiency	Increase in productivity, improvement in working conditions, increased material efficiency, labour productivity, more controlled conditions for weather, improved supervision of labour, easier access to tools, fewer material deliveries, decrease in disputes during construction	Musa et al. [2], Lu et al. [34], Zhang et al. [48], Bortolini et al. [50]
Reduced construction time	Reduced time, improvement of the speed of construction, shortened completion times	Zhang et al. [48], Arashpour et al. [49]
Reduce construction cost	Reduced costs, reduction of the overall cost of construction, the opportunity for producing complex building components at a lower cost, saving on-site construction labour, decreased labour	Yuan et al. [39], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]; Pan and Pan [5]
Environmental sustainability	Sustainability due to less waste, reduced damage to environment and ecosystem, less air and sound pollution, reduction of the construction waste, reduction of the environmental impacts, reduction of construction waste, reduced wastage, reducing environmental burdens, fewer job-site environmental impacts because of reductions in material waste, air and water pollution, dust and noise, and overall energy costs, reduction of the environmental impacts to residents around construction sites	Musa et al. [2], Lu et al. [34], Yuan et al. [39], Zhang et al. [48], Bortolini et al. [50]
Better working condition	Improvement of working conditions and health and safety of the workers, safety, better worker safety, improve safety	Musa et al. [2], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]; Pan and Pan [5]
Better product sustainability	Lower maintenance and repairs, higher sustainability performance, workmanship, workflow continuity, flexible	Musa et al. [2], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]

Table 3. Hindrance factors for DfMA/prefabrication application.

Hindrance Factor/Challenges	Item	Authors
Awareness	Lack of awareness of the implication of using new technologies	Musa et al. [2], Trinder [26], Gbadamosi et al. [46], Charlson and Dimka [51]
	Lack of construction knowledge	Chen and Lu [22], Gao et al. [33], Gbadamosi et al. [46]
	Lack of staff training	Gao et al. [33], Charlson and Dimka [51], Lu et al. [34]
	Lack of comprehension of the requirements to fulfil off-site manufacturing business strategy	Charlson and Dimka [51]

Table 3. *Cont.*

Hindrance Factor/Challenges	Item	Authors
Acceptance	Acceptance of stakeholders	Musa et al. [2], Chen and Lu [22], Pan and Pan [5], Charlson and Dimka [51], Langston and Zhang [52], Lu et al. [34]
	Dependence on conventional methods	Pan and Pan [5]
	Resistance to change, community mindset	Charlson and Dimka [51], Langston and Zhang [52], Lu et al. [34]
	Readiness	Musa et al. [2]
	Bad perception based on historic accounts	Trinder [26]
	Trapped as labour-intensive industry instead of technology-intensive	Tik et al. [37]
	Foreign workers could delay the technology engagement and development	Tik et al. [37]
Cost-effectiveness	High start-up cost	Trinder [26], Zhang et al. [48], Pan and Pan [5], Tik et al. [37], Gao et al. [33], Charlson and Dimka [51], Rosarius and de Soto [53]
	Volumetric construction needs to secure sufficient order to break even	Tik et al. [37]
	Lack of economy of scale	Shang et al. [54]
	Limited demand	Trinder [26]
Design limitation	Limited design flexibility and requires early design freeze	Trinder [26]
	Inflexible for design change, long design time, long lead time	Zhang et al. [48], Bortolini et al. [50]
	Suppliers often contribute too little during the early-stage design	Gbadamosi et al. [46]
	Order modifications that arise in the short-term lead	Rosarius and de Soto [53]
	Increase in design time	Shang et al. [54]
Logistic issues	Transportation difficulties, damage during transportation	Trinder [26], Shang et al. [54], Rosarius and de Soto [53]
	Small working area, restricted site access	Trinder [26]
	Lack of storage space	Zhang et al. [48]
	Underutilization of factory space	Pan and Pan [5]
	Transportation distance	Langston and Zhang [52], Rosarius and de Soto [53]

Table 3. *Cont.*

Hindrance Factor/Challenges	Item	Authors
Contract and supply chain issues	Traditional contracting forces sequential engineering and separation of design and construction	Trinder [26]
	Early involvement of subcontractors and suppliers does face challenges in the contracting practices	Gao et al. [33]
	Unanticipated conflicts among different trades on-site	Bortolini et al. [50]
	Complex supply chain resources, such as manufacturing plants, assembly equipment, and crews, supply chain management	Bortolini et al. [50], Langston and Zhang [52]
	Payment terms; contractors only pay for products when it is delivered to the site and fully installed	Shang et al. [54]
	Adapting existing procurement models obstructs the potential benefits of using off-site technologies	Charlson and Dimka [51]
	Supply change management	Langston and Zhang [52]
Proof of concept	Inability to select the appropriate project for DfMA trials	Trinder [26]
	Few cases of DfMA application to show the actual benefits	Lu et al. [34]
	Insufficient R&D expenditures	Gao and Tian [55]
	Lack of adequate information to evaluate the potential benefits and constraints of using off-site construction	Gbadamosi et al. [46]
	Inconsistent product quality	Pan and Pan [5]
Integration difficulties	Integration difficulties between DfMA products and existing on-site assets	Trinder [26],
	Complex interfacing	Pan and Pan [5]
	High level of uncertainty when the product is not completely defined	Bortolini et al. [50]
	Information fragmentation	Li et al. [4], Pan and Pan [5]
	Scheduling complexity	Pan and Pan [5]
	Compatible building type	Langston and Zhang [52]
	Lack of suitable ecosystem, which includes guidelines, standards, and affordable technologies	Lu et al. [34]

Table 3. *Cont.*

Hindrance Factor/Challenges	Item	Authors
Guidelines, standards, and policies	New innovative solutions may sit outside current standards, leaving clients vulnerable to operational risks	Trinder [26], Lu et al. [34]
	Lack of necessary government regulatory efforts to promote prefabricated construction	Gao and Tian [55]
	No legal framework available for off-site manufacturing	Charlson and Dimka [51]
	Lack of government regulations and incentives	Langston and Zhang [52]
	Planning and building codes, lack suitable guidelines, and standards	Langston and Zhang [52]
	Some guidelines are proposed in a fragmented fashion without necessarily forming an organic whole, leading to a lack of comprehensiveness, or "easy to use" throughout the building process	Lu et al. [34]
	Available guidelines are based on manufacturing context without sufficiently considering the best fit for construction adaptation	Lu et al. [34], Tan et al. [38], Rosarius and de Soto [53]

Previous authors have discussed the hindrance factors and challenges for either DfMA or prefabrication and they are listed in Table 3 above. Noticeably, most of the challenges listed in adopting DfMA are similar to the hindrance factors for adopting prefabrication. However, there are challenges more specific to DfMA highlighted by several authors, which include:

- The multidisciplinary team does not fulfil the expectations;
- Standardisation limits design flexibility and requires early design freezes;
- Traditional contracting forces sequential engineering and the separation of design and construction;
- Staff training;
- Suppliers often contribute too little during early-stage design;
- Design involves an increase in time;
- Lack of planning and building codes;
- Lack of a suitable ecosystem that includes guidelines, standards, and affordable technologies;
- New innovative solutions may sit outside current familiar standards, leaving clients vulnerable to operational risks;
- There are too few data on the DfMA application to show the actual benefits.

The application of DfMA in the construction industry requires a paradigm shift for all stakeholders. The essential objective of DfMA needs to be properly digested and understood to garner its full potential. As described in the earlier section of this paper, DfMA is a design principle and method to optimise product manufacturing and assembly. To start the adoption of DfMA in the construction industry, available guidelines from the manufacturing industry might be the best reference. However, such guidelines need further study to better suit the construction industry. This should also include the evaluation of whether DfMA is suitable for a specific project. DfMA must not be rejected in a project just because of the perception induced by demands of off-site prefabrication. There are other options, such as on-site prefabrication and modular in situ fabrication, that could be made better with the application of DfMA principles. Understanding where DfMA is appropriate and where it is not is key.

4.4. The Enabling Factors for DfMA Application in the Construction Industry

To increase the acceptance of DfMA in the construction industry, certain enabling factors need to be considered. Enablers, such as knowledge of DfMA [21,48], supporting technologies [52,56,57], preferable government policies [55,58], and suitable procurement methods and contracts [48], could increase the interest in the application of DfMA in the construction industry.

Knowledge of DfMA is important for creating awareness and for the industry players to have an interest in it. Project owners are seen as being more interested in methods that enhance quality and reduce waste, with lesser risk and conflicts. Though the initial cost might be higher, advanced technology and integrated methods of project delivery are thought to be value-adding and forward-thinking approaches [59]. DfMA would likely match the mentioned features where DfMA focuses on enhancing the efficiency of fabrication and assembly of building parts [60].

To avoid fragmentation, projects need early engagement among all stakeholders to be successful because the earlier changes are made in the early stage of design or project inception, the less costly [61]. In construction, what has been designed will affect most of the project cost, but the cost of the design phase itself is usually less than 10% of the project cost [62]. Therefore, the application of DfMA at the design stage of a project with a full-time coordinator looking to collaborate with contractors, architects, and other consultants could help to optimise the construction project's performance [21]. Such understanding and awareness could only be achieved by knowing how things work in the construction industry and how it could benefit from DfMA.

A project involves a multidisciplinary team. Principles or methods such as DfMA intend for them to be involved from the early design stage. Only certain procurement methods could allow this. The design and building procurement method means that the appointed contractor is tasked to manage the design process and carry out the construction works. Such a procurement method is seen as the preferred method to implement prefabrication, thus implementing DfMA principles [48]. The management cost of such a practice should be considered in selecting the procurement method. Selecting those that should be on the team must be in tandem with implementing the principles or methods. The team members must be those who can make the decision making efficient [22]. The procurement method and standard form of contract is an area that needs more study in forming a stable legislation basis for the practice of DfMA or any other principles similar to it.

A redesign process that includes inventive problem solving by looking at specific design tasks and adding in solutions from an identified database of designs or technologies would make the application of principles such as DfMA work better [45]. The design process should adopt a digital and parametric platform so that it can be completed more efficiently to cope with changes. BIM is an example of such a platform that is expanding in the construction industry [22,35,41]. The inclusion of a digital system such as BIM would help in the design process [63]. To make DfMA work throughout the whole project cycle, the design process should include the delivery process and tower cranes or any other on-site machinery assembly requirements, and BIM could also help in this area [21].

BIM's ability to model and create simulations is highly beneficial in decision making [64]. Modelling and simulation would enable designers and stakeholders to evaluate the methods used in construction activities by representing the actual construction and simulating the cause and effect of a system before the actual construction is undertaken [4,65]. This could lead to producing a digital twin for a project.

BIM could also be useful in tracking the off-site manufacturing and on-site assembly by integrating it with identification and positioning technologies, such as radio frequency identification (RFID) and global positioning systems (GPSs). Information gathered in the BIM platform could then be shared with all relevant stakeholders for better management and quicker decision making [57,66]. All data collected from the various project by an organization would be beneficial in the future. Therefore, the usage of product data management (PDM) is essential in the design and manufacturing practice. This ensures the data are readily available for the next job [67]. By establishing a library of design data, the design process could be performed faster. The library should consist of proven and untested product data for future references [52,62]. With iterations of multi-criteria decision making (MCDM) involved in the design process, the library data and tools, such as the weighted sum method, analytic hierarchy process, and technique for ordered preference, could make the process easier and quicker [68].

To support the principles of DfMA, government policies, such as those in China, Singapore, and Malaysia, are important for supporting the adoption of prefabrication [35,58]. However, a high level of prefabrication might not be all good. The key is to have the optimal level that fits into the specific construction environment and considers the political, economic, social, and technological factors [6]. Policies with incentives and support have proven to be effective in increasing the uptake of new innovative methods, such as prefabrication and DfMA, as opposed to directive policies [55,58]. The type of more effective incentives and the delivery method needs more study to enable the formation of better policies regarding DfMA.

The DfMA principles, which are often linked to prefabrication, would see higher adoption when there is a higher demand for prefabrication projects. Marketing strategies for prefabrication products would therefore have an impact on DfMA adoption [48]. In creating the demand, policies and guidelines are essential. The rules, principles, and best practices of DfMA should be spread out to building designers. Pioneers in DfMA for construction, such as the Royal Institute of British Architects (RIBA), have created an overlay to their plan of work. Singapore's Building and Construction Authority (BCA) has identified DfMA as part of the strategy to increase the productivity of construction. BCA also published guidelines for prefabricated prefinished volumetric construction (PPVC) to promote the practice [33]. A flexible construction method, such as semi-modular off-site prefabrication and DfMA, would benefit smaller companies by not having to come out with a big investment of setting out large prefabrications [69]. Combining all these findings to form better guidelines for DfMA for construction is what the industry needs. This could enhance the understanding and uptake of DfMA.

The usage of manufacturing machines in construction has a considerably high investment cost. However, if a project workflow is recurring and the machines could be used across several projects, a positive return on investment is possible. In turn, this would make it highly possible to have a safer, cleaner, and quicker construction method with DfMA principles in place [70]. Data produced from academic study and actual practice could help to convince the industry players. Therefore, all the enablers need to be tabled out and studied to produce more convincing data. The enablers for DfMA can be summarised in Table 4.

Table 4. Summary of enablers for DfMA/prefabrication application.

DfMA Enabler	References	Example
Knowledge	Gao et al. [23], Trinder et al. [62], Banks et al. [21], Zhang et al. [48]	Knowledge of DfMA for all stakeholders, guidelines
Supporting organization	Gao et al. [23], Chen and Lu [22]	Supplier, designer, RIBA
Government support	Gao et al. [23], Jin et al. [35], Wang et al. [58], Lu et al. [34], Gao and Tian [55]	Policies, incentives, legislation, investment, guidelines
Stakeholders	Nguyen and Akhavian [59], Trinder et al. [62], Banks et al. [21], Chen and Lu [22]	Multidiscipline design team, clients, developers, contractors, suppliers
Technologies	Basarir and Cem Altun [45], Chen and Lu [22], Jin et al. [56], Yuan et al. [39], Banks et al. [21], Li et al. [4], Pinheiro et al. [65], He et al. [57], Merja and Harri [67], Langston and Zhang [52], Trinder et al. [62], Tan et al. [38]	BIM, RFID, GPS, PDM, MCDM, IoT
Project-specific factors	Gao et al. [33], Vaz-Serra et al. [69]	Transportation route, site storage, material

All of these enabling factors would be essential in promoting the application of DfMA in the construction industry. This could increase the demand for DfMA and, in turn, make the technology surrounding its application more affordable. With technology integrations and DfMA know-how, the construction industry would see better performance in the future in terms of quality, time, and cost.

Figure 5 shows that to improve the uptake of the DfMA principles in the construction industry, it requires a combination of the enablers listed in Table 5, including better knowledge to create awareness, supportive policies to boost demand, and good guidelines to make it easier to apply. When it comes to BIM and other related technologies, the current practice in the construction industry should not be far off from what is needed to implement the DfMA principles.

Applying collected data from Sections 4.2–4.4, the conceptual framework in Figure 6 gives an overview of the proposed direction and what is needed to make the application of DfMA in the IBS project and the construction industry more effective.

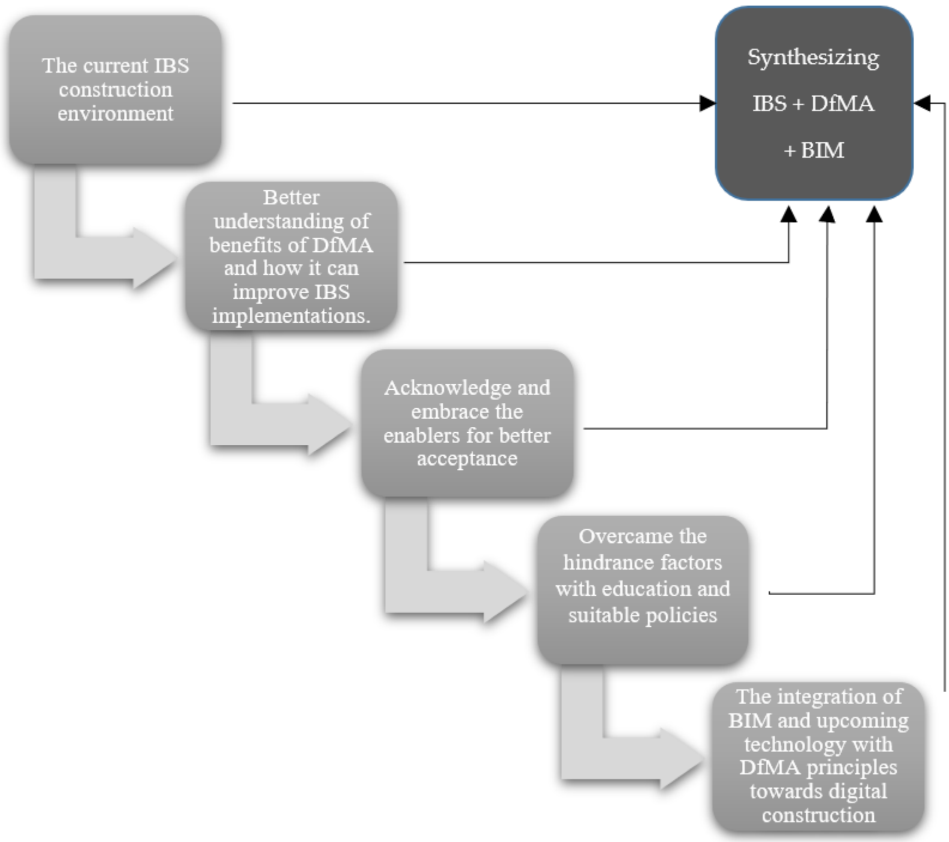

Figure 5. Synthesising DfMA principles with IBS and BIM.

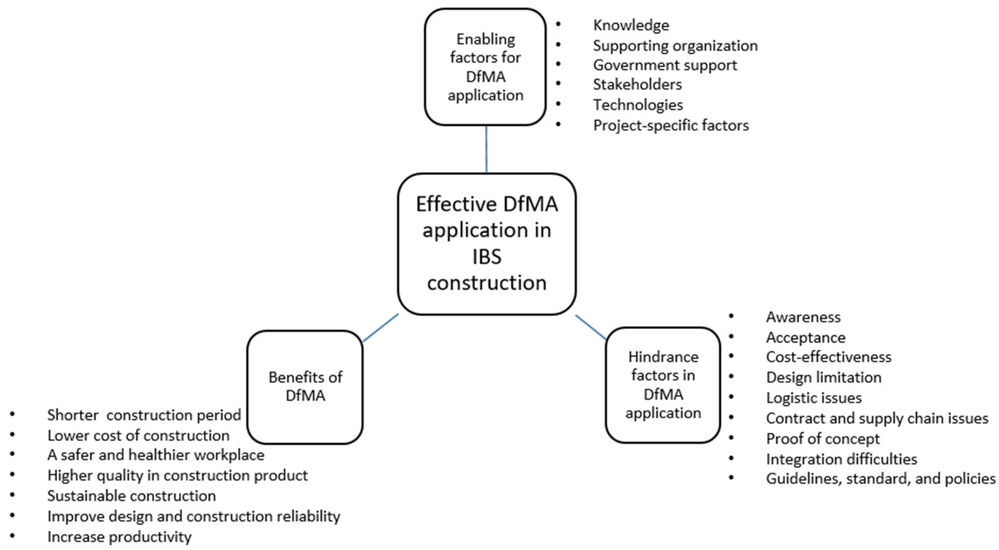

Figure 6. A conceptual framework for DfMA application.

Table 5. Summary of research themes related to DfMA/prefabrication.

Id	Research Theme	Authors
1.	DfMA/Prefabrication integration with other principles or technology 18 articles	Mesa et al. [36], Li et al. [66], Merja and Harri [67], Pinheiro et al. [65], Yuan et al. [39], Zhao et al. [10], Bensalah et al. [71], Bortolini et al. [50], Gbadamosi et al. [60], Li et al. [4], Nguyen and Akhavian [59], Tetik et al. [72], Alfieri et al. [73], Gbadamosi et al. [46], He et al. [57], Wang et al. [58], Xing et al. [74], Bakhshi et al. [28]
2.	DfMA/Prefabrication application 14 articles	Banks et al. [21], Basarir and Cem Altun [45], Chen and Lu [22], Gao et al. [23], Trinder [26], Trinder et al. [62], Tik et al. [37], Jin et al. [35], Gao et al. [33], Wasim et al. [43], Ferreira et al. [44], Lu et al. [34], Vaz-Serra et al. [69], Hyun et al. [20]
3.	Prefabrication construction method/tools 7 articles	Musa et al. [2], Orlowski et al. [75], Fardhosseini et al. [70], Pan and Pan [5], Mesa et al. [76], Favi et al. [47], Liu et al. [77]
4.	Prefabrication material 6 articles	Oktavianus et al. [78], Orlowski et al. [25] Liew et al. [79], Orlowski [80], Orlowski et al. [81]
5.	Prefabrication drivers/barriers factor 4 articles	Zhang et al. [48], Shang et al. [54], Bao et al. [82], Langston and Zhang [52]
6.	On-site construction technology based on DfMA 3 articles	Martinez et al. (2013), Li et al. [7], Rosarius and de Soto [53]
7.	Supply chain and resource management for prefabrication 2 articles	Arashpour et al. [49], Arashpour et al. [83]
8.	Policies and legislation 2 articles	Gao and Tian [55], Charlson and Dimka [51]
9.	Optimal prefabrication	Lu et al. [6]
10.	DfMA guidelines	Tan et al. [38]

5. Discussion

5.1. Research Themes, Trends, and Gaps

The research theme of each of the articles is grouped according to their research focus, as shown in Table 5. The research themes are divided into 10 groups with the largest group, containing 19 articles, discussing the integration of DfMA or prefabrication with other principles or technology. Containing 14 articles, the next highest group involves discussions of the application of DfMA or prefabrication in various capacities. These two groups combined would represent more than half of the pooled articles. This shows that the main focus of this research domain is now on the condition of DfMA or prefabrication adoption and the technology and other principles that could be integrated to make the process better.

The least studied area is the optimal prefabrication and DfMA guidelines. These two areas, from what has been discussed in the two articles, are essential in developing working policies that would make DfMA principles more appealing. Optimal publication arguments from Lu et al. [6] ensure that the practice should only be applied according to the requirements of a project and not only to make up the number of prefabrication-based projects. This would ensure the purpose of having a prefabrication-based project stay true to the cause. The guidelines discussed by Tan et al. [38] would help the construction industry to better understand the principles of DfMA and not only depend on the guidelines produced based on the manufacturing sector. The construction industry is unique and this should be considered to revamp it from all sides.

A time-based research trend was developed based on the information gathered, limited to the articles referred to in the current study. This trend will hopefully provide a better understanding of the development of research conducted on DfMA principles and prefabrication in the context of the construction industry. Figure 7 shows the current research trend and the future path of this research domain. The research trend characterises research themes that have developed over the years, forming a few dominant research areas. This research topic is relatively new and currently involves a rather small group of researchers.

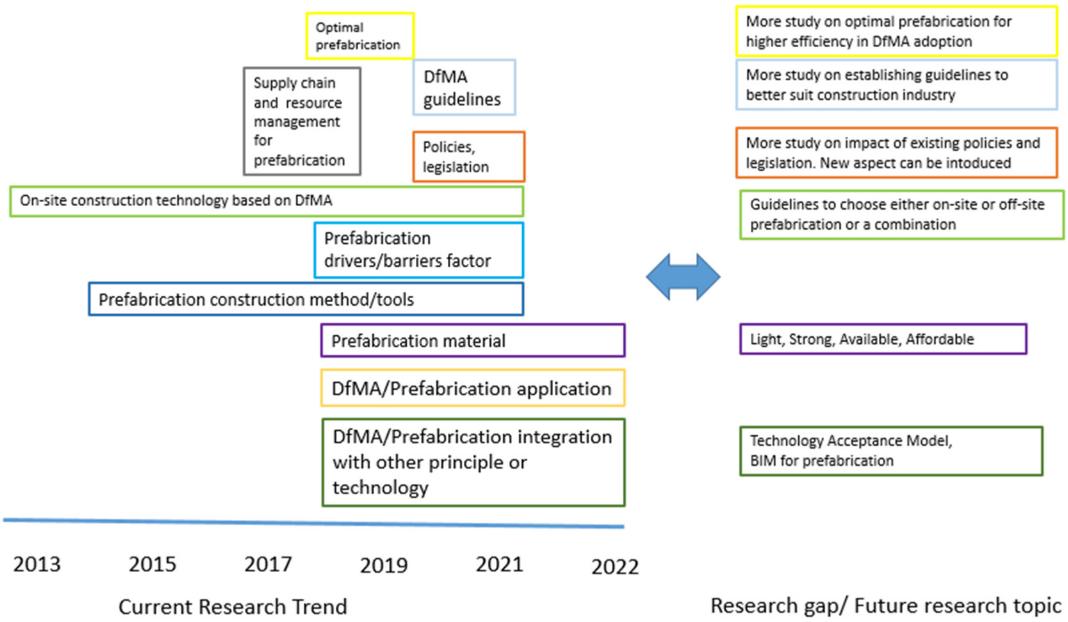

Figure 7. DfMA research framework based on trends of research theme.

From the discussions, the layout of the research theme and research trend and the research gap were identified. In Figure 7, the knowledge gaps and the potential future research topic are listed on the right and aligned with the research theme.

5.2. The Research Gap and Potential Future Research Topic

By synthesising the findings of the previous paper, this review paper can fill the research gap and provide suggestions for a future research topic. The gap is identified in several areas: (1) guidelines on DfMA application; (2) data management; (3) policies, incentives, and litigation; and (4) overall application of DfMA principles.

5.2.1. Guidelines on DfMA Application

In an effort to introduce innovative ways to increase construction performance, the risk of such innovation must be evaluated. The characteristic of a project that is suitable for on-site or off-site prefabrication needs to be set and included in the guidelines so that the innovation can be accepted and improve the industry instead of creating superficial benefits.

Construction-oriented DfMA guidelines are needed since the existing guidelines are manufacturing-based; therefore, they lack some features that fit well with the construction industry. Aspects such as natural, cultural, and geospatial data should be considered to be included in the guidelines. Technologies proposed also need to be specifically efficient for a typical project. The supply chain is of importance since construction projects usually involve lots of materials and the logistics must be taken care of. The design process usually does include the consideration of materials to be used and should be natural for the DfMA design method. DfMA usually involves modular or building components design; the integration of each part should also be considered to suit each project delivery condition. Another characteristic that should be considered is transportation. Off-site prefabricated modular or building parts transportation should be within the allowable margin of cost, time, and certain legislation restrictions. Logistic management must be efficient and reliable, taking into consideration all the different activities involved to avoid activities that do not add value to the project.

Most discussions about DfMA are focused on off-site prefabrication. There should also be guidelines for on-site fabrication and prefabrication since not all projects are suitable for off-site construction but can still benefit from DfMA design principles.

These proposed guidelines would also mean recognising which party should be included in the design team from the start of the project. They need to have a holistic view of the design that could make manufacturing and assembly better.

5.2.2. Data Management

Product data management (PDM) and BIM are tools proven to be beneficial for DfMA and the prefabrication process. However, data updating should be made automatic as the design continues so that there are no issues with inundated design data that would then defeat the purpose of PDM.

The usage of BIM in helping organise the prefabrication of creating modular and building parts has been acknowledged by several researchers. However, BIM systems are more familiar with conventional construction. Therefore, the BIM system needs to be adjusted to better suit DfMA and the prefabrication method, especially in recognising all of the jointing elements as part of the building. Even though the possible application of BIM to improvise the DfMA method of design has been mentioned by several researchers, there is still not much data that can support the claim. Hence, there is a need to further examine the adoption of BIM into the DfMA and prefabrication method.

5.2.3. Policies, Incentives, and Litigation

Studies on policies, incentives, litigation, and contractual matter regarding DfMA are still lacking. Clear related policies and strategies are available in the United Kingdom and Singapore, while Hong Kong lines up guidelines and incentives. Discussion on the right incentives needs to be lengthened to see if it benefits the right parties. Since these aspects are crucial in realising the uptake of DfMA, it is only logical that more studies need to be done, especially with the diverse aspect of construction all over the world. Procurement methods and forms of contract should also be kept updated and be suitable for the DfMA principles.

5.2.4. Overall Application of DfMA Principles

As a whole, the overall usage of DfMA in construction is relatively still new and low. Even though the concept was popularly used in the 70s, its adoption in the construction industry has only started quite recently. DfMA as design analysis is not fully applied and is not applied on all construction components. Analysis data of the benefits of DfMA are also few and cannot be definitive enough to convince further investment. The small number of studies makes the information needed to apply DfMA in the construction industry rather scarce. More studies are needed to obtain more knowledge on the practical adoption of DfMA in construction.

5.3. Limitations

This study is limited to the relevant studies on DfMA in construction based on a topic search result in the Web of Science and Scopus databases. This study is also limited to articles that have mentioned DfMA in the title, abstract, or main text. Future studies could include articles from other databases and other search criteria. It would also be beneficial for future studies to be carried out as systematic literature reviews and bibliometric studies on relevant articles.

6. Conclusions

The application of DfMA in projects using IBS has many benefits. The objective of IBS in enhancing the productivity of constructions could be achieved by implementing DfMA. More projects could be delivered on time with better construction quality. Additionally, the usage of DfMA in the IBS project could also increase the potential of making the construction industry more sustainable by reducing construction waste. Applying DfMA in the construction industry would also increase its ability to be transformed into an automated industry, especially during the manufacturing process. Enhanced with integration with technology, such as BIM and GPS, DfMA has the potential to bring the construction industry into the digital world. This will lead to more effective and sustainable constructions.

Despite the clear advantage of applying DfMA in the construction industry, more research needs to be done. In Malaysia's context, DfMA is still very vague. There is very little research performed on strategizing and developing guidelines for the application of DfMA in the construction industry. This study could help the construction industry analyse and evaluate the optimal ways of adopting new innovative solutions such as DfMA. From the previous studies, the identified benefits of DfMA should be reason enough to apply it in the construction industry. Using the data compilations presented in this study, we can identify what is required to apply DfMA in the construction industry. From the conceptual framework produced in this study, strategies and guidelines could be developed for the optimal application of DfMA.

More data collection and proper presentation of the data analysis could provide a better understanding and a strong argument for championing DfMA adoption in the construction industry. This means that more studies need to be carried out to obtain the required data. A better understanding of the benefits of DfMA and its true potential would make it more acceptable to the players and stakeholders in the construction industry.

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Abbreviation

The following abbreviation is used in this manuscript.

DfMA	Design for manufacturing and assembly
BIM	Building information modelling
IBS	Industrialised building system
RFID	Radio frequency identification
GPS	Global positioning system

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