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Review

Design for Manufacturing and Assembly (DfMA) in Construction: A Holistic Review of Current Trends and Future Directions

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Abstract: The construction industry, despite its anticipated significant growth, has struggled with low productivity over the past two decades. Design for manufacturing and assembly (DfMA), a methodology with a history of success in other industries, presents a promising solution to enhancing efficiency in construction. This article reviews the current state of DfMA in the construction industry, identifies the most recent research themes in the field of DfMA, and provides recommendations for future DfMA research based on the existing research gaps. The paper employs a mixed-method approach, combining quantitative bibliometric analysis and qualitative thematic analysis. Using Scopus as the literature database, the study identified 43 relevant articles published between 2013 and 2023. The bibliometric analysis reveals a growing interest in DfMA research, with an upward trend in publications over the years. The thematic analysis categorizes DfMA research topics into six main themes: Innovation and Technology Trends, Sustainability and Environmental Impact, Regulatory and Policy Considerations, Collaborative Approach, Applications, Benefits, and Challenges, and Project Lifecycle. Each theme is explored in-depth, providing insights into the transformative impact of technology, environmental considerations in DfMA, regulatory challenges, collaborative strategies, varied applications, and the project lifecycle phases influenced by DfMA. The article concludes by presenting identified research gaps and offering recommendations for future DfMA research. It emphasizes the need for a holistic approach, continued collaboration, and a focus on unexplored aspects of regulatory frameworks and the entire project lifecycle. This study sets a new benchmark in DfMA research by employing a novel mixed-method approach and providing unprecedented insights into the multifaceted role of DfMA in advancing construction industry practices. It serves as a valuable resource for researchers, practitioners, and stakeholders in the construction industry by offering a comprehensive understanding of DfMA's current state and guiding future research endeavors.

Keywords: design for manufacturing and assembly (DfMA); off-site construction (OSC); construction productivity; automation

Citation: Montazeri, S.; Lei, Z.; Odo, N. Design for Manufacturing and Assembly (DfMA) in Construction: A Holistic Review of Current Trends and Future Directions. *Buildings* **2024**, *14*, 285. https://doi.org/10.3390/buildings14010285

Academic Editor: Salvatore Antonio Biancardo

Received: 18 December 2023
Revised: 15 January 2024
Accepted: 17 January 2024
Published: 20 January 2024

1. Introduction

Globally, construction sector productivity has grown at a slower rate, 1% per year over the past two decades, compared to the overall world economy at 2.8%, and manufacturing at 3.6%. Furthermore, less than 25% of construction firms have matched the productivity growth of the economies in which they operate [1]. To improve productivity and sustainability in the construction industry, design for manufacture and assembly (DfMA), which was developed over 50 years ago and has been widely used since the 1980s, offers promise in simplifying product design and increasing efficiency and cost savings [2]. Ref. [3] defines DfMA as a methodology designed to address the issue of fragmentation within the construction industry. It achieves this by promoting early collaboration among design, manufacturing, and construction teams through the combination of the principles of design for manufacturing (DfM) and design for assembly (DfA).

Throughout the automotive, aerospace, mechanical, and other manufacturing industries, the DfMA approach has been extensively used for decades. It has only been in recent years that the Architecture, Engineering, and Construction (AEC) industries have begun exploring DfMA [4]. DfMA principles in the construction industry can be used by designers to enhance the buildability of products at a very early stage of design [5,6]. DfMA, as a methodology, is centered on the utilization of guidelines, criteria, and principles. several authors have proposed that DfMA can be effectively implemented by introducing various policies, such as the minimization, standardization, and modularization of assembly parts [7].

According to ref. [6], DfMA offers similar benefits in manufacturing and construction. According to a survey of DfMA users conducted by Boothroyd Dewhurst, Inc., typical realized benefits include: a 51% reduction in parts count, a 37% decrease in parts cost, a 50% faster time to market, a 68% improvement in quality and reliability, a 62% drop in assembly time, and a 57% reduction in manufacturing cycle time. In recent years, a growing number of studies have paid attention to DfMA-oriented design, specifically among modular and prefabricated construction projects, and different review studies have been conducted in this field. In a literature review conducted by ref. [6], the focus was directed toward the dynamic landscape of DfMA within the construction industry. By addressing the evolving trend of combining off-site prefabrication with onsite assembly, the review identifies a noticeable gap in the existing literature concerning a comprehensive understanding of DfMA, its potential, and associated challenges in the construction domain. A recent study by ref. [5] included a literature review of DfMA implementation, with a focus on industrialized building systems and the Malaysian construction industry. In addition, a review article by ref. [8] explored the significance of DfMA within the AEC industry, attracting the attention of designers, practitioners, and stakeholders in construction projects. It specifically explores the integration of Digital Fabrication (Dfab) and Design for Additive Manufacturing (DfAM) practices. In another study by ref. [7], through a literature review, the applications and benefits of DfMA and DfD in construction were identified and discussed. This study also addresses recent developments and research gaps in the fields.

Despite the growing focus on DfMA, a gap in the literature still exists regarding a thorough review of DfMA, its possibilities, and the challenges it presents in the construction domain. Although some studies have explored specific aspects of DfMA within construction, a comprehensive overview that encompasses the different stages of DfMA research is notably missing. It is crucial to achieve a holistic overview of the present context, identify areas with limited research, and outline future research directions for DfMA. With a holistic approach, this study will achieve the following objectives: (1) implement a bibliometric analysis to highlight the current status of DfMA in the construction industry; (2) identify the most recent research themes in the field of DfMA over the past ten years; and (3) identify the research gaps and provide recommendations for future DfMA research.

In the following sections of this paper, the various aspects of the research will be explored. Section 2 will present a detailed exploration of the research methodology employed in the study. In Section 3, a comprehensive bibliometric analysis is conducted, shedding light on the current state of DfMA in the construction industry. In Section 4, a thematic analysis will be performed, identifying the most recent research themes related to DfMA over the past decade. Section 5 is dedicated to a thorough discussion of the research findings, and the significance and implications within the context of DfMA are analyzed. Following this, Section 6 synthesizes the research gaps and outlines future directions for DfMA research, offering valuable insights to guide forthcoming studies. Lastly, in Section 7, a concise summary of the key insights and contributions generated throughout the study is provided, offering a cohesive and structured exploration of our research ito DfMA within the construction industry.

2. Research Methodology

Reading and understanding relevant literature is essential for researchers to gain a deeper understanding of a particular topic [9]. In developing the methodology for this study, we carefully considered the contributions of previous and contemporary scholars to ensure the approach was robust and relevant. To conduct a comprehensive review, following a systematic literature review (SLR) method was crucial. As outlined in ref. [10], the SLR methodology encompasses procedures for collecting, organizing, and evaluating literature within a specific review area. "Collecting" involves identifying and obtaining relevant literature, "organizing" entails systematically categorizing and refining the literature, and "evaluating" focuses on the analysis and presentation of findings from the literature.

The methodology of this study is based on a mixed-method approach, which consists of quantitative and qualitative methods to achieve the research objectives. Based on the process described in studies by ref. [11,12], a meticulous search using specific keywords, guided by inclusion and exclusion criteria, was conducted. This comprehensive review served as the basis upon which the subsequent phases of the research were developed.

To enhance the precision of our research approach, we employed both bibliometric and thematic analysis. The bibliometric analysis, supported by the VOCviewer 1.6.19 software, consistent with the study by ref. [13], underscores the importance of such analysis in understanding the impact of research within a field. Similarly, the thematic analysis adheres to the procedures detailed by ref. [14], involving iterative coding and the categorization of emerging themes from the literature. This method enables the distillation of the information obtained from the literature review into coherent patterns and trends relevant to the research questions. The paper will also discuss future research areas based on identified DfMA research gaps. In conclusion, we provide recommendations for both researchers and practitioners. Figure 1 summarizes the methodological process employed in this study.

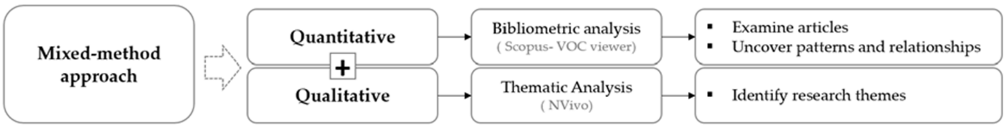

Figure 1. Methodological process.

In this research, Scopus was chosen as the literature database for conducting a comprehensive study of journal papers in English between 2013 and 2023. According to ref. [15], Scopus is acknowledged as one of the largest research publication databases available. In comparison to other databases, it offers a broad spectrum of high-quality publications covering the construction domain and various interdisciplinary research areas. To ensure a high level of quality, this study does not include conference proceedings, but only peer-reviewed articles published in construction-related journals. The keyword search strategies, which were used to identify relevant articles, involved selecting keywords for DfMA research. This was achieved based on a thorough review of previous papers concerning DfMA definitions and concepts. This bibliometric research began by inputting these keywords into Scopus, as explained below:

("Design for manufacturing and assembly" OR "DfMA" OR "design for manufacture and assembly" OR "design for manufacture" OR "design for assembly")

The PRISMA diagram illustrating the literature search process for the DfMA methodology in general, along with the assessment of the inclusion criteria, presents the initial DfMA search. This initial search was narrowed down by specifically looking for DfMA-related articles in the construction field, while publications covering subject areas that did not fall within the scope of the study were excluded. At the subsequent stage, a deep scanning of the title, abstracts and keywords, and a document scan, was carried out. This was done to help select relevant and valid publications for the literature review. This refinement reduced the total number of relevant articles to 43. The PRISMA diagram for the process of selecting articles is shown in Figure 2.

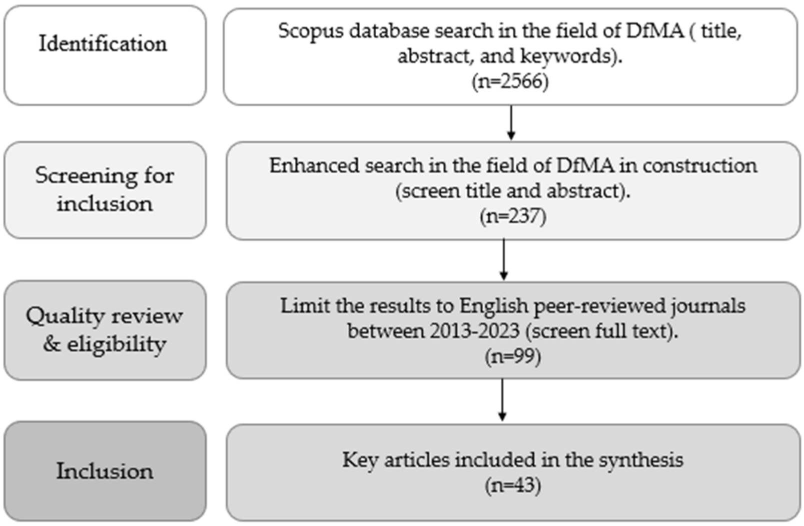

Figure 2. Journal article selection using PRISMA diagram.

Following the completion of the cleansing, analysis, and synthesis of data from existing studies, we employed the VOS viewer computer program for quantitative analysis. The VOC viewer is a program we have used for building and visualizing bibliometric maps that is freely accessible to the bibliometric research community [13]. According to ref. [13], the VOS viewer can be utilized to create author or journal maps using co-citation data, or to generate keyword maps based on co-occurrence data. The software facilitates the viewer in a thorough examination of bibliometric maps.

After completing the bibliometric analysis and science mapping, a qualitative analysis was conducted to assess the current areas of research concentration in DfMA. This included identifying the main research themes in the field of DfMA and offering suggestions for upcoming research in this domain according to the existing research gaps.

Qualitative data analysis can be enhanced with Qualitative Data Analysis Software (QDAS) tools, which have been developed to assist researchers and are available to the public [16]. According to [17], QDAS assists researchers in reading and interpreting large volumes of academic papers and other texts as part of the literature review process. As a result, they can create links, visualize connections, and identify areas for further research. We used NVivo™14, which is one of the most persistently used QDAS programs [16]. This qualitative data analysis software facilitates the collection, categorization, mapping, analysis, and visualization of qualitative data [18].

3. Bibliometric Analysis

A comprehensive bibliometric search focusing on DfMA literature was conducted on Scopus, employing a set of pre-selected DfMA-specific keywords. This search identified a total of 2566 journal articles. The refined search for articles specifically related to DfMA in the construction field included an enhanced title and abstract screening, reducing the number of relevant articles to 237. This subset underwent a rigorous quality review process, whereby only articles from English peer-reviewed journals published within the last ten years were considered, further reducing the pool to 99 articles. The final inclusion stage involved a meticulous synthesis of the data, culminating in 43 key articles that were most pertinent to the DfMA in construction. These articles were expected to provide a robust foundation for understanding the current state of DfMA within the industry, as well as offer insights into future directions and innovations in the field.

3.1. Distribution of Article by Year and Journal

A line graph is shown in Figure 3 that represents the number of documents published per year from 2013 to 2023 in the field of DfMA in construction. The graph shows a general upward trend in publications over the years, with a significant increase in the last two years, indicating growing interest and research in DfMA. Thus, it can be concluded that the research outputs at DfMA are expected to grow in future years based on the current trend. The source of this DfMA-related journal paper was also identified using Scopus analysis. Figure 4 illustrates that all journals have increased their cite scores over the years, which could be indicative of a growing body of research and increased citations in the field of construction and civil engineering, and among the journals, Automation in Construction has the highest number of articles (The data presented in Figure 4, extracted from Scopus, cover from 2011 to 2022).

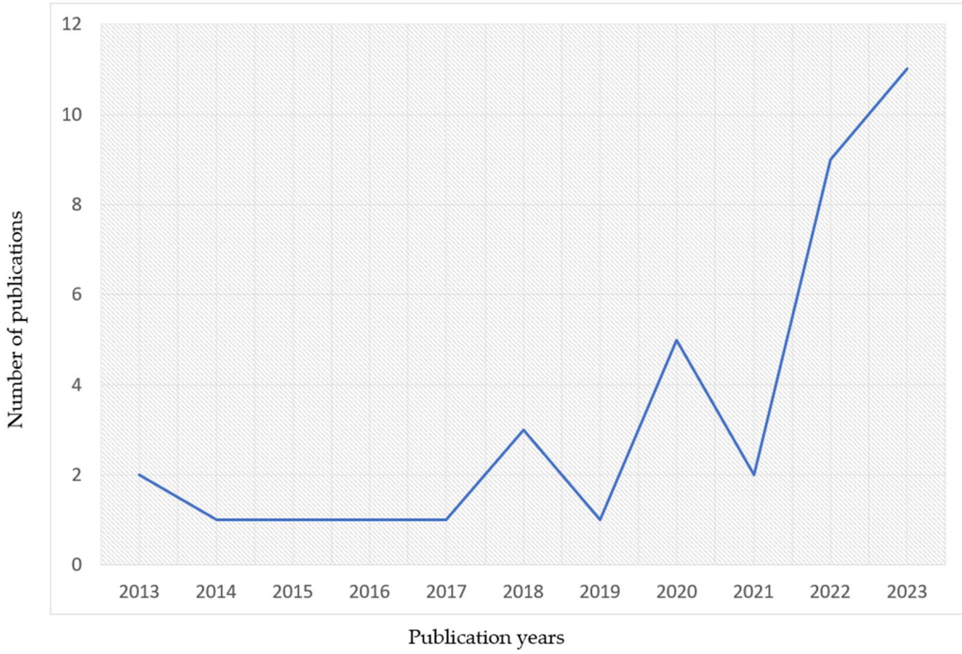

Figure 3. Distribution of articles by year.

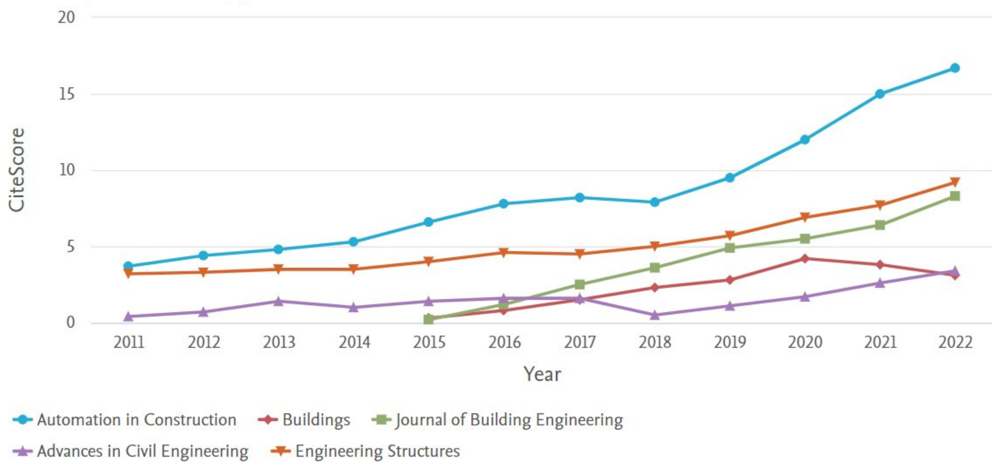

Figure 4. Distribution of articles by journal.

3.2. Countries Active in DfMA Research

In this section, we analyzed the number of articles by country of affiliation of the first author (Figure 5). This distribution indicates that the United Kingdom is the most dominant in this field, followed by South Korea and China, with Hong Kong contributing the least within this dataset. This can reflect the focus and investment of different countries or territories in the field of DfMA in construction.

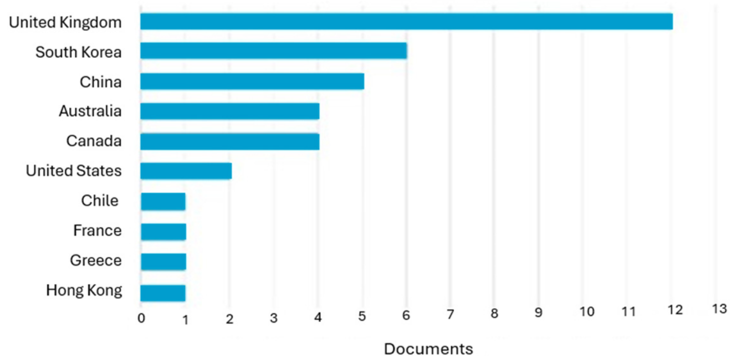

Figure 5. Countries active in DfMA research.

3.3. Citation of Articles

The researchers aimed to identify publications that had a significant influence on the research community. With a minimum citation threshold of 30, six articles out of the total pool met this requirement. Table 1 displays these articles along with their respective citation counts. The research by ref. [19], "Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings", focuses on addressing the challenge that many design systems face when applied to prefabricated buildings. The paper proposes the integration of DFMA into prefabricated building design. This involves combining DfMA with the parametric design of BIM to create a concept and process for DFMA-oriented parametric design. A review paper by ref. [6] is the second most cited article in the field of DfMA. This signifies the widespread recognition and influence of their work, indicating that the research conducted has significantly contributed to shaping the discourse around and understanding of DfMA within the construction industry. Their comprehensive review has likely served as a valuable reference for researchers, practitioners, and professionals seeking insights into the processes, principles, and perspectives of DfMA, further establishing their paper as a cornerstone in the literature on this evolving field.

Table 1. List of publications with the highest impact in DfMA.

Author	Title	Number of Citations
[19]	Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings	157
[6]	Design for Manufacture and Assembly in construction: a review	77
[20]	Big Data for Design Options Repository: Towards a DFMA approach for offsite construction	40
[21]	An approach for sustainable, cost-effective, and optimized material design for the prefabricated non-structural components of residential buildings	39
[22]	Flexible Field Factory for Construction Industry	35
[23]	Integrated BIM and DfMA parametric and algorithmic design-based collaboration for supporting client engagement within offsite construction	31

The paper by ref. [20] is the third most cited in the field of DfMA. It addresses the challenge of the limited information available for assessing prefabrication alternatives and supplier choices in offsite construction. The researchers propose a Big Data Design Options Repository (BIG-DOR) that integrates BIM, DfMA, and Big Data. BIG-DOR aims to connect BIM clients with manufacturers'/suppliers' information. The study presents a framework for integrating BIG-DOR into OSC, including the architecture and key components. The significant contribution is the successful integration of BIM, Big Data, DfMA, and OSC, resulting in a design alternatives assessment system that will promote OSC adoption.

3.4. Co-Occurrence of Keywords

As highlighted by ref. [13], a network of keywords serves to illustrate knowledge in terms of relationships, patterns, and the intellectual organization of research themes. Among all finalized articles from the bibliometric search, we set author keywords in the VOC viewer 1.6.19 and word search frequency query in NVivo™14, considering inclusion and exclusion criteria such as removing the general keywords, and other keywords with semantically consistent meanings were combined, for example, offsite construction, off-site construction, and offsite; finally, a total of 25 main keywords were shortlisted and visualized in Figure 6. The identified 25 DfMA keywords serve as the foundation for categorizing the main research topics into different distinct areas. By doing this, our research can comprehensively explore the six interconnected categories informed by the extensive collection of DfMA keywords we identified.

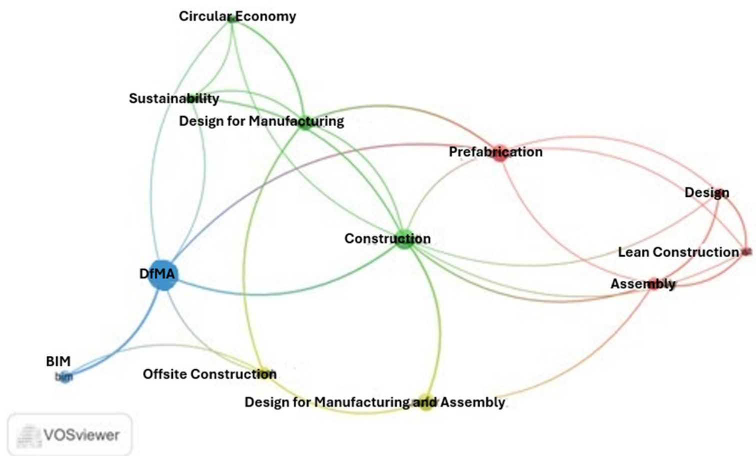

Figure 6. Co-occurrence of keywords in DfMA research.

Firstly, keywords such as "Design", "BIM", and "Technology" inherently align with the realm of Innovation and Technology Trends. In this context, our investigation might delve into how these elements are shaping the future of construction methodologies and the impact of cutting-edge technologies on the built environment. Moving on, keywords such as "Quality" and "Sustainability" directly point to an exploration of how DfMA can contribute to environmentally friendly and resource-efficient construction practices under the Sustainability and Environmental Impact research theme. This category could involve assessing the life cycles of different construction projects and their potential to minimize environmental footprints. Keywords like "Regulatory", "Integrated", and "Management" naturally lead us to the category of Regulatory and Policy Consideration. Our research may explore how regulatory frameworks and management approaches can be adapted to incorporate the evolving landscape of DfMA, ensuring compliance and fostering efficient integration into existing construction practices.

The Collaborative Approach category can be linked to keywords such as "Development", "Structural", and "Collaborative". Here, the focus might be on understanding how collaborative models and interdisciplinary approaches enhance the overall efficiency of DfMA projects. Application Area is closely tied to keywords like "Building", "Construction", and "Application". This category could involve investigating specific domains wherein DfMA principles find optimal applications, such as residential construction, infrastructure projects, or commercial building developments. The Lifecycle category, encompassing "Performance", "Framework", and "Optimization", could explore the entire life cycle of structures built with DfMA, assessing their long-term performance, adaptability, and opportunities for optimization throughout their existence.

4. Thematic Analysis

In addition to the bibliometric analysis of articles in the field of DfMA, this study conducted a thematic analysis of the identified themes using a qualitative approach. Text coding was performed through NVivo™14 software, and descriptive themes were developed according to a study by ref. [24]. The purpose of this thematic analysis was to highlight our findings in the following three categories: (1) to summarize the main research topics; (2) to analyze the performance of DfMA based on these categorizations; and finally, (3) to provide recommendations for future research according to the existing research gaps. Thematic analysis, as a qualitative method, clarifies data content through a systematic classification process involving coding and theme identification. This approach not only facilitates the organization of data, but also enables the generation of new interpretive constructs and explanations grounded in the underlying themes of variables [25].

As demonstrated in the preceding section, the classification of research subjects primarily relies on the keyword analysis conducted in the science mapping (see Figure 6 and Table 2) and continues with the pedagogy of N7+1, which was proposed by [14] for writing literature reviews with the support of NVivo™14 software in eight steps. According to ref. [14], the N7+1 series of actions guides the researcher from database exploration to literature analysis, eventually leading to writing the review. Figure 7 illustrates the steps we followed.

Table 2. DfMA's most frequently studied keywords.

DfMA Keywords	Count	Weighted Percentage (%)
Design	5059	2.02
Construction	4134	1.65
Assembly	1963	0.78
Manufacturing	1600	0.64
Building	1429	0.57
Prefabricated	1258	0.50
BIM	1152	0.46
Technology	739	0.30
Information	938	0.37
Integrated	669	0.26
Management	644	0.26
Approach	564	0.22
Development	555	0.22
Structural	516	0.21
Offsite	486	0.19
Performance	460	0.18
Quality	456	0.18
Framework	454	0.18
Modular	454	0.18
Application	419	0.17
OSC	418	0.17
Digital	364	0.15
Guidelines	334	0.13
Optimization	321	0.13
Sustainability	314	0.13

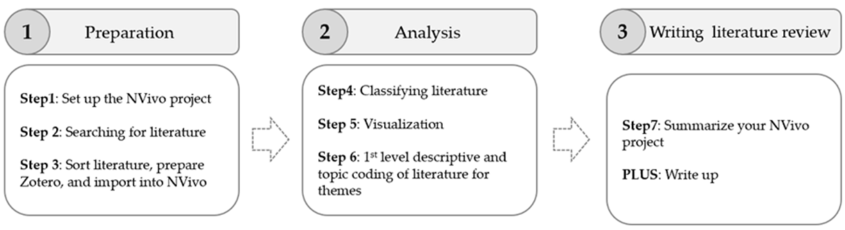

Figure 7. The complete N7+1 sequence of steps.

Through the implementation of keyword analysis and the coding process facilitated by NVivo™14 software, this study contributes novel findings that serve to help identify key research areas associated with DfMA. The identified DfMA research themes discussed throughout this section, as described by Figure 8, encompass the following categories: innovation and technology trends; sustainability and environmental impact; regulatory and policy considerations; collaborative approach; applications, benefits, and challenges; project lifecycle.

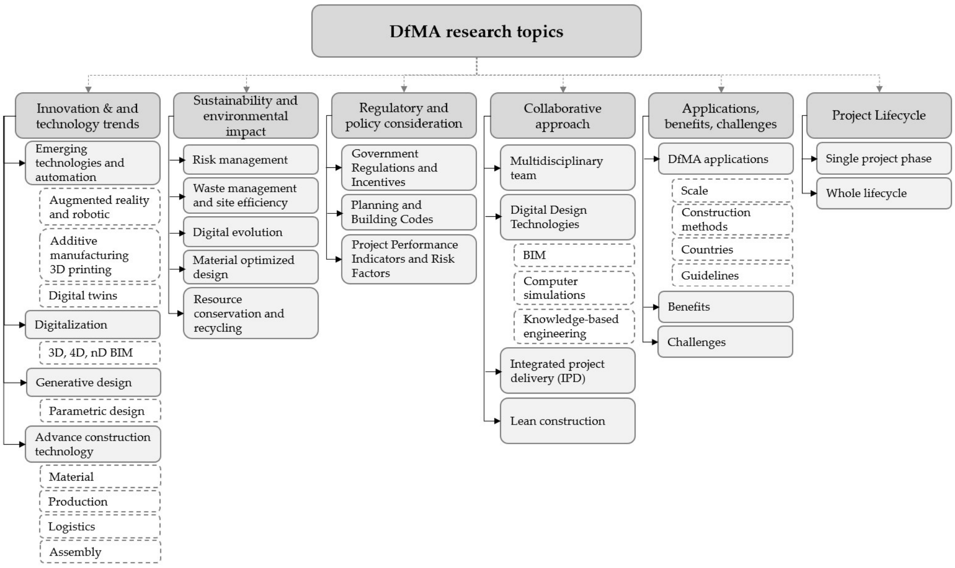

Figure 8. DfMA research topics.

5. Discussion

5.1. DfMA Research Topics

In delving into the diverse domain of DfMA, our research has identified six main themes that form the foundation of this investigation. Through the lens of Innovation and Technology Trends, Sustainability and Environmental Impact, Regulatory and Policy Considerations, Collaborative Approach, Application Area, Benefits and Challenges, and Project Lifecycle, we employed NVivo™14 to conduct a comprehensive analysis of the existing literature presented in Figure 9.

The hierarchy chart generated using NVivo™14 provides a visual representation of the key DfMA topics extracted from our selected articles. At the top of the list, we observe "Innovation and Technology Trends", indicating a significant emphasis on staying updated with technology advancements within the DfMA domain. Following closely are "Application Area, Benefits and Challenges", suggesting a focus on practical DfMA implementation. "Sustainability and Environmental Impact" and "Collaborative Approach" underscore the parallel importance of environmental concerns and collaborative dynamics inherent in DfMA practices. Accordingly, our analysis reveals that "Regulatory and Policy Considerations" and "Project Lifecycle" emerge as relatively less emphasized topics within the domain of DfMA research covered in the reviewed articles. While acknowledging the influence of regulatory frameworks on the DfMA processes, and understanding the different stages in a project's lifecycle, it becomes apparent that these aspects are not as extensively addressed as other key points in the literature. This observation suggests that the reviewed articles may lean more towards exploring other dimensions of DfMA. The next section focuses on a qualitative analysis, providing detailed insights into these DfMA topics.

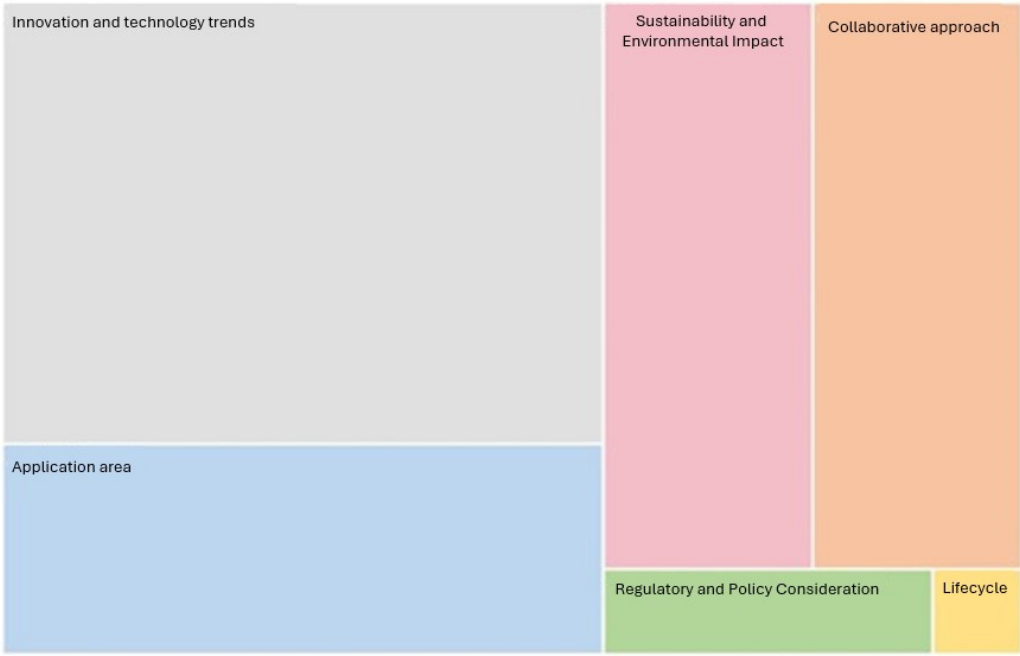

Figure 9. Hierarchy chart of code comparisons in selected articles, based on the amount of coding assigned to them.

5.1.1. Innovation and Technology Trends

DfMA is a rapidly developing field with a profound impact derived from various innovations and technological trends. The findings of this research align with those of several scholars, including refs. [7,11,21,26], who emphasize the transformative impact of emerging technologies and automation in DfMA. Most notably, augmented reality, additive manufacturing and digital twins have reshaped the design and execution of construction projects. This perspective is reinforced by the analysis of this research.

In the analysis of innovation and technology trends within DfMA, digitalization emerged as a sub-theme. This encompasses various dimensions of digital construction technologies, including 2D, 3D, and 4D applications. While this study highlights the potential use of digital construction technologies in enhancing DfMA practices, it is essential to acknowledge that diverse viewpoints exist among scholars in this domain. On one side, a significant body of research has underscored the transformative impact of digital construction technologies on DfMA. For instance, studies have demonstrated the potential of these technologies for use as valuable tools for improving DfMA implementation on various construction projects, ranging from commercial-scale endeavors [2] to OSC projects [24–26], Among the plethora of digital tools and platforms available, numerous articles emphasize the promising synergy that arises from integrating BIM-based approaches with DfMA principles. This integration not only guides designers and suppliers, but also enhances the manufacturability and assimilability of construction projects [22,27,28]. Furthermore, a body of literature delves into the development of BIM-based frameworks tailored to address challenges such as information interoperability, conflict detection, and requirement checking. These frameworks aim to refine the DfMA process as a whole, offering potential solutions to long-standing issues in the field [17,29–31].

Another notable sub-theme that has garnered attention is generative design, specifically its application in addressing challenges within the AEC industry. According to ref. [27], generative design, exemplified by techniques such as building component combination algorithms, represents a paradigm shift in how we approach and tackle industry challenges. It is imperative to acknowledge that the inclusion of generative design in DfMA practices comes with varying viewpoints within the scholarly community. Notably, scholars such as ref. [32] have underscored the potential of generative design in revolutionizing construction projects by optimizing design processes and creating more efficient structures. Ref. [27] also proposes that by integrating DfMA principles at early design stages, we can use the full potential of generative design technology in construction projects. Lastly, there is a focus on advanced construction technologies, encompassing materials, production, assembly, and logistics, all of which collectively contribute to a holistic approach aimed at enhancing DfMA efficiency and effectiveness. Our research underscores the pivotal role of advanced construction technologies in shaping the future of DfMA. In particular, we acknowledge the work of scholars such as ref. [25], who argue that materials with improved properties, innovative production techniques, streamlined assembly processes, and efficient logistics are at the forefront of advancing DfMA principles. The perspective of ref. [25] aligns with our findings, emphasizing the need to embrace these technological advancements for the successful implementation of DfMA.

However, it is important to note that not all scholars share this view; [6], for instance, presents an alternative perspective, suggesting that while advanced construction technologies are promising, their adoption in DfMA should be approached cautiously [6], and they highlight potential challenges related to cost-effectiveness, scalability, and the need for specialized skills in implementing these technologies effectively. This debate within the DfMA research community raises critical questions about the practicality and feasibility of fully integrating advanced construction technologies into DfMA practices. While our study leans towards the optimistic view of their potential, we acknowledge the validity of concerns raised by scholars like [6,32]. These differing viewpoints encourage further research and discussions within the field, emphasizing the dynamic nature of DfMA and the evolving role of technology.

5.1.2. Sustainability and Environmental Impact

Several studies have explored the general concept of sustainability within DfMA. Ref. [28] highlights how DfMA can contribute to a more sustainable form of construction. In the field of sustainability and environmental impact within DfMA, a comprehensive exploration of crucial sub-themes reveals various dimensions. Firstly, the integration of risk management practices appears essential for ensuring long-term sustainability. Recognizing the operational risks associated with new technologies, a study conducted by ref. [29] emphasized the necessity for effective risk management throughout an asset's lifecycle.

Secondly, an important aspect of environmental practice revolves around waste management in construction, a perspective shared by ref. [7], who emphasize the significance of addressing challenges related to insufficient waste management practices. In line with the findings of this research, [7] proposes sustainability assessment studies to evaluate the environmental impact of DfMA, emphasizing initiatives aimed at reducing vehicle movements and improving on-site logistics efficiency [28].

Moreover, within the field of sustainability and environmental impact, our identified sub-theme of digitalization is underscored by the literature, including [2]. The authors propose a transformative framework that places a significant emphasis on digital construction practices, highlighting their potential to yield smarter outcomes, particularly in terms of sustainability and environmental impact.

One of the additional sub-themes identified within the overarching theme of sustainability and environmental impact is material-optimized design, a concept supported by prior research. For instance, [28] demonstrates DfMA's potential to make substantial contributions to environmentally friendly construction practices through sustainable and material-optimized designs, particularly in the context of prefabricated 3D steel structures. This alignment with previous research highlights the significance of material-optimized design as a key component of sustainable DfMA practices.

Lastly, the sub-theme of resource conservation and recycling aligns with prior scholarly research. Ref. [29] delves into the broader sustainability theme by underscoring the pivotal role of DfMA in resource conservation, recycling, and overall environmental sustainability. Their in-depth exploration elucidates how a thoughtful design approach for production and assembly can significantly influence recycling practices and the preservation of raw materials, thus further aligning with the overarching goal of sustainability. This correlation with previous research substantiates the importance of resource conservation and recycling as integral components of DfMA's contribution to environmental sustainability. These insights collectively contribute to a deeper understanding of sustainability and environmental considerations in the DfMA context.

5.1.3. Regulatory and Policy Consideration

Regulatory and policy considerations represent a relatively less-explored facet within the extensive field of DfMA research. The analysis of this theme aligns with the existing literature, shedding light on several critical sub-themes. In a study conducted by [2], the authors meticulously investigated the multifaceted barriers impeding the widespread adoption of DfMA. Their research strongly emphasizes government regulations and incentives, as well as the influence of planning and building codes. Identifying these regulatory challenges becomes imperative to comprehensively address the complexities that obstruct the seamless integration of DfMA practices. Additionally, in another enlightening study by [30], the authors identifies project performance indicators and risk factors specifically within the context of prefabricated prefinished volumetric construction (PPVC). The insights gleaned from this exploration significantly enrich the understanding of regulatory and policy considerations in the realm of DfMA. This alignment with previous research further underscores the importance of addressing regulatory and policy aspects to advance the field of DfMA effectively.

5.1.4. Collaborative Approach

The collaborative approach in DfMA is multifaceted, as evidenced by various research articles. Ref. [30] underscore the significance of an operative multidisciplinary team for effective DfMA implementation, while [6,33] also contribute to the field by emphasizing stakeholder collaboration in the design process of industrialized timber construction systems.

Examining digital design technologies, one of the important factors in the collaborative approach to DfMA in construction, ref. [30] delves into the potential challenges raised by the absence of digital design technologies during the DfMA implementation. Aligning with this perspective, Ref. [2] suggests a collaborative strategy that integrates BIM tools with lean construction processes. This proposition demonstrates the synergy between collaborative approaches and digital design technologies, specifically aiming to optimize outcomes. Expanding the scope of collaboration, [34] shed light on the collaborative approach needed in integrating DfMA with computer simulation in product development, emphasizing the importance of a systemic view across different aspects of the production system. Ref. [35] contributes by focusing on the collaborative use of Knowledge-Based Engineering applications and their role in informing designers about manufacturability aspects and performance expectations, which emphasize the role of digital design technologies in the field of DfMA in construction.

Moving towards collaborative strategies, Ref. [36] argues for a collaborative system involving the integration of DfMA principles with lean construction to assess and optimize building design elements. Ref. [37] connects DfMA with integrated project delivery and collaborative efforts, further emphasizing the diverse dimensions of collaboration within DfMA research. These research articles collectively present a comprehensive overview of the collaborative approach in DfMA, connecting multidisciplinary team collaboration, the integration of digital design technologies, collaborative strategies like lean construction, and integrated project delivery, into a cohesive exploration of the multifaceted nature of collaboration within the DfMA framework.

5.1.5. Applications, Benefits, and Challenges

DfMA has emerged as a critical approach in the construction industry, with different applications and numerous benefits and challenges in the architecture, engineering, and construction (AEC) industry. The literature review yields a rich collection of insights from various studies, each contributing to a better understanding of DfMA applications, advantages, and challenges. Various studies zoom in on specific application areas within the construction industry. According to ref. [37], DfMA methods have a wide range of applications, including small-scale and large-scale construction projects, as well as cast-in-place and prefabricated construction methods. However, in most of the reviewed articles, it is expected to be adopted most widely in prefabricated projects. The literature shows that a variety of articles establish the significance of applying DfMA principles as a transformative philosophy, such as in the following: embracing prefabrication technologies with practical applications [15,18,29,38] in different OSC projects with various materials in construction, focusing on non-structural components [21]; the use of prefabricated facades [35]; volumetric steel structures for modular building construction [39]; innovative approaches toi Prefinished Prefabricated Volumetric Construction (PPVC) [40], and the use of precast concrete [41]. Ref. [38] emphasizes the need for the early integration of manufacturing and assembly principles for improvements in design efficiencies and cost savings. The studies consistently position DfMA as a methodology capable of tackling various challenges and limitations within the prefabrication process. Problems may include inadequate detail in prefabricated components/connections or complex component design [19]. DfMA-oriented design, as suggested by these studies, can address these problems by incorporating manufacturers and technicians in the initial stages. This proactive approach involves the careful consideration of potential problems during the subsequent phases of manufacture and assembly. Consequently, DfMA is recognized as a pivotal and indispensable step in the prefabrication process, as emphasized in the study of ref. [37].

Ref. [42] specifically focuses on the construction industry in Singapore and the application of DfMA technologies within this context, while [28] cites a successful DfMA project in the UK, and ref. [43] develops a revised DfMA workflow for the Italian AEC sector, showcasing the varied application of DfMA in different countries. Other studies explore the application of DfMA in the construction industry, emphasizing the need for construction-oriented DfMA guidelines that consider context, technology rationalization, logistics optimization, component integration, and material-lightening to improve the benefits and address the challenges of implementing DfMA [44].

The data collected support the perception that DfMA can deliver significant improvements in productivity, time efficiency, cost management, reliability, quality, and safety in construction projects [7,28,32]. Ref. [29] emphasizes that DfMA contributes not only to economic gains but also to health and safety improvements [29]. Various research studies also examine challenges in DfMA implementation within the construction industry. These challenges encompass issues such as inefficiencies within multidisciplinary teams, constraints in design standardization, traditional contracting approaches, insufficient training, the absence of a supportive ecosystem, and delays involving suppliers at the early stages of a project [8,32].

5.1.6. Project Lifecycle

Throughout the lifecycle of a construction project, there are a number of stages that must be completed in order to achieve the project goal. Several studies have shown that the DfMA method has a positive effect on various project phases [6,37,45]. According to the RIBA (2020), the different stages of a construction process are defined as: definition, preparation and briefing, concept design, spatial coordination, detailed design, manufacturing/construction, handover, and use/operation. Although there are studies with a focus on the implementation of DfMA in the whole lifecycle of the project [39], according to ref. [46], most studies have examined DfMA's impact with the most attention being given to design, manufacturing, and site assembly.

6. Research Gaps and Future Directions in DfMA Research, a Comprehensive Synthesis

In advancing the understanding and applications of DfMA, this synthesis draws upon a myriad of insightful literature. By identifying research gaps, each piece of literature offers unique perspectives and suggestions for future research. The combination of these diverse insights forms a cohesive roadmap for the future direction of DfMA research.

6.1. Innovation and Technology Trends

Regarding innovation and technology trends, Ref. [2] highlights the need for advanced digital construction and engineering capabilities to facilitate the adoption of DfMA, indicating a gap in understanding how these capabilities can be effectively leveraged. Therefore, the study can conclude that future research endeavors should delve into the practical implications of advanced digital construction and engineering capabilities, and explore how these can be harnessed to facilitate and optimize the adoption of DfMA principles in construction practices.

In a more detailed view, a gap exists in our understanding of how cutting-edge digital technologies such as AI, blockchain, and IoT can be seamlessly integrated to enhance future progress in DfMA research. Refs. [32,47] emphasize the pivotal role of these technologies in reshaping DfMA practices. To address this gap, future research should focus on exploring the practical implementation and synergy of AI, blockchain, and IoT in DfMA. This exploration can uncover new opportunities for enhancing efficiency, precision, and connectivity throughout the construction process.

Another research gap is identified in the integration of DfMA with digital fabrication techniques. According to ref. [48], digital fabrication primarily involves the five methods used in architecture: (1) additive manufacturing (AM), (2) subtractive manufacturing (SM), (3) formative manufacturing, (4) joining manufacturing, and (5) robotic manufacturing. The research findings of ref. [49] indicate that while some of the digital fabrication techniques like AM offer advantages such as design freedom and accelerated building rates, time-saving may not always be the most significant advantage in the construction context. The study suggests that the cost implications of design changes, the type of geometries used, and production volumes play crucial roles in determining the suitability of digital fabrication techniques for construction projects.

While some studies have explored the integration of DfMA with digital fabrication techniques [50], such as three-dimensional (3D) printing technology using cement-based materials (3D printing is an additive manufacturing process [51]), there is a common understanding, as highlighted by ref. [49], that future research directions should prioritize the optimal integration of DfMA with these digital fabrication techniques. This entails the development of guidelines that effectively combine DfMA principles with digital fabrication techniques in construction projects, with project-specific considerations.

Ref. [2] identifies a gap in the optimization of logistics and supply chain management within the context of DfMA, pointing to the instrumental role of technologies like laser scanners, Auto ID, QR/bar codes, and data analytics. Future research should concentrate on leveraging and integrating technologies such as laser scanners, Auto ID, QR/bar codes, and data analytics to optimize logistics and supply chain management in DfMA. This focus can lead to streamlined processes, real-time tracking, and data-driven decision-making, enhancing DfMA's implementation efficiency and effectiveness. Collectively, these technological advancements form a dynamic foundation for DfMA's future, promising a convergence of innovation and practical application within the construction landscape.

6.2. Sustainability and Environmental Impact

The lack of a comprehensive sustainability assessment approach for structures constructed through the DfMA methodology, as emphasized by ref. [7], underscores the need for a deeper understanding of its ecological implications. So, future research should focus on developing robust sustainability assessment frameworks specifically tailored to structures built using the DfMA methodology. This involves exploring the environmental impact throughout the entire lifecycle of such structures.

The need to integrate circularity in construction, focusing on recycling materials and deploying smart decision-making tools, as highlighted by ref. [32], points to a gap in integrating circular economy principles into DfMA practices. Future research endeavors should focus on incorporating circular economy principles into DfMA practices, emphasizing the recycling of materials and the integration of smart decision-making tools to enhance resource efficiency and environmental sustainability. This approach will guide future DfMA projects toward more eco-friendly construction methodologies.

6.3. Regulatory and Policy Consideration

The current lack of standardization and clear policies in the field of DfMA poses a challenge, as highlighted by ref. [7]. There is a pressing need for construction-oriented DfMA guidelines to ensure a systematic approach to implementation. To address this gap, future research should focus on the development of regulatory and policy frameworks for DfMA. Building on the argument of ref. [7], the emphasis should be on standardization and policy development to provide a structured foundation for DfMA implementation. This entails exploring the potential synergies between Integrated Project Delivery (IPD) and construction-oriented DfMA, with empirical investigations needed to understand the administrative intricacies and benefits of this collaborative approach.

The studies conducted by refs. [31,36] contribute to regulatory analyses by delving into organizational structures and contractual frameworks related to DfMA. These analyses underscore the importance of establishing a robust regulatory framework for DfMA projects. Expanding on these insights, future research should delve deeper into organizational structures and contractual frameworks in DfMA projects. The focus should be on developing comprehensive regulatory guidelines that consider the aspects highlighted by refs. [31,36]. This research direction aims to further explore the necessity of a comprehensive regulatory framework to guide the construction industry toward standardized practices and collaborative methodologies in DfMA projects.

6.4. Collaborative Approach

The need for a holistic understanding and application of DfMA is underscored by ref. [30], emphasizing the importance of comprehensive case studies. However, there is a research gap in exploring the specific challenges and opportunities associated with implementing collaborative approaches in DfMA within the construction environment. To address this gap, future research should delve into the complexities of collaborative approaches in DfMA, examining the challenges and opportunities through in-depth case studies. This exploration can provide valuable insights into how collaboration among diverse stakeholders can be optimally leveraged for successful DfMA implementation.

The study by ref. [7] highlights the necessity of collaborative information-sharing systems operating on multiple levels for the success of DfMA. Yet, there is a gap in understanding the practical strategies and frameworks required to establish and sustain such collaborative systems for DfMA implementation. Future research endeavors should focus on developing practical strategies and frameworks for the establishment and maintenance of collaborative information-sharing systems that operate on multiple levels. This will contribute to creating a roadmap for effective collaboration in DfMA, ensuring its success across various projects.

Ref. [31] underscores the interconnectedness of project evaluation processes and collaborative endeavors, emphasizing the importance of collaboration in achieving impactful and efficient project assessments within proposed BIM workflows. However, there is a research gap in understanding how collaborative approaches can be systematically integrated into BIM workflows for enhanced project assessments in the context of DfMA. To fill this gap, future research should focus on systematically integrating collaborative approaches into BIM workflows for DfMA projects. This entails exploring how collaboration can be optimized within BIM processes to enhance project evaluations, ensuring a more streamlined and efficient implementation of DfMA principles.

6.5. Application, Benefits, and Challenges

According to a study by ref. [29] that proposes a DfMA scoring tool, there is a research gap related to the importance of refining and optimizing the practical application of the scoring tool to ensure its efficacy and reliability in diverse construction contexts. So, the future research should focus on conducting comprehensive validation studies of the DfMA scoring tool using real case studies and projects. This involves assessing its performance and applicability in different construction scenarios to enhance its practical application.

There is a need for an in-depth exploration of the diverse application scenarios of DfMA across different construction settings and building types, as emphasized by ref. [30]. This research gap underscores the importance of understanding how DfMA can be effectively applied in various contexts.

According to this, researchers should delve into diverse application scenarios of DfMA, exploring its implementation across different construction settings and building types. This multifaceted exploration will contribute to uncovering the benefits and challenges associated with DfMA methodologies, providing valuable insights for tailored approaches in distinct construction scenarios.

Understanding the contextual factors influencing the success and challenges of DfMA remains an unexplored area. This gap is identified in ref. [37], and suggests the need for a comprehensive examination of the contextual elements impacting the application of DfMA. It can be concluded that future research should aim to uncover and analyze the contextual factors that influence the success and challenges of DfMA. This exploration will contribute to a more comprehensive understanding and effective utilization of DfMA in diverse construction contexts.

6.6. Project Lifecycle

To address the existing gaps in research and to advance the application of DfMA, future research should center on a holistic understanding and application of DfMA principles across various stages of the project lifecycle. The current understanding of DfMA's impact throughout the project lifecycle is limited, focusing primarily on individual phases. So, future research should prioritize a holistic examination of DfMA principles across different project lifecycle stages, as emphasized by ref. [29]. There is also a lack of exploration of DfMA-oriented design beyond pre-fabrication, indicating a gap in understanding the full scope of DfMA. Building on the work of ref. [37], future studies should expand their exploration of DfMA-oriented design beyond prefabrication. The research should delve into broader applications of DfMA, considering design aspects beyond prefabrication and aiming to improve production efficiency while aligning with sustainability objectives. The objective is to foster environmentally conscious construction practices through a more comprehensive understanding of DfMA's potential impact.

7. Conclusions

In conclusion, this comprehensive review of DfMA in the construction industry reveals a promising path towards enhancing efficiency and sustainability. The paper employs a mixed-method approach, combining quantitative bibliometric analysis and qualitative thematic analysis to explore the current state of DfMA research.

The bibliometric analysis highlights a growing interest in DfMA research, with an upward trend in publications over the years. Automation in Construction emerges as the leading journal for DfMA-related articles, and the United Kingdom stands out as the most prolific country for DfMA research. The thematic analysis categorizes DfMA research into six main themes: Innovation and Technology Trends, Sustainability and Environmental Impact, Regulatory and Policy Considerations, Collaborative Approach, Applications, Benefits, and Challenges, and Project Lifecycle.

Each theme is explored at depth, providing insights into the transformative impact of technology, environmental considerations, regulatory challenges, collaborative strategies, varied applications, and the project lifecycle phases influenced by DfMA. The paper identifies key research topics, and emphasizes the need for a holistic approach, continued collaboration, and a focus on unexplored aspects of regulatory frameworks and the entire project lifecycle.

The research methodology, combining bibliometric analysis and thematic analysis, proves effective in providing a comprehensive understanding of the current status of DfMA in the construction industry. The paper concludes with valuable recommendations for future DfMA research, serving as a valuable resource for researchers, practitioners, and stakeholders in the construction industry. The findings underscore the potential of DfMA to drive positive changes in the construction sector, addressing challenges and unlocking new opportunities for enhanced productivity and sustainability.

7.1. Limitation of the Study

This study has limitations that open up avenues for future research, including:

- The study's findings are based on the analysis of existing research articles, which may not fully represent the entire spectrum of DfMA practices and developments within the construction industry. The results are specific to the literature analyzed and may not necessarily reflect the entire industry's current state;
- The study focuses on articles published between 2013 and 2023. This specific time frame was chosen to narrow the focus to up-to-date literature, as DfMA is an evolving field and recent developments are of particular interest. However, it is important to acknowledge that by narrowing the analysis to this time frame, this may inadvertently omit earlier influential research;
- The analysis includes articles published in English, which might introduce a language bias. Relevant research in other languages could offer different perspectives and findings that were not considered in this study.

Despite these limitations, this study serves as a valuable starting point for understanding the current state of DfMA in the construction industry, offering insights into research themes, trends, and areas requiring further exploration. Researchers and practitioners should consider these limitations when interpreting the findings and designing future research endeavors.

7.2. Recommendations for Future DfMA Research

As we conclude our analysis, it becomes clear that DfMA offers significant opportunities for improving efficiency and sustainability in construction. However, achieving this potential necessitates the establishment of a clear path for future research efforts. This section outlines a roadmap for future DfMA research, guided by the six thematic areas that have emerged from our analysis. Each of these areas represents a crucial facet of DfMA, and our recommendations aim to guide researchers, practitioners, and stakeholders toward productive inquiries that will further enrich our understanding and application of DfMA principles in the construction industry.

Innovation and Technology Trends:

- Explore the practical implications of advanced digital construction and engineering technologies;
- Investigate the integration of cutting-edge digital technologies such as AI, blockchain, and IoT into DfMA practices;
- Prioritize the optimal integration of DfMA with digital fabrication techniques, including the development of guidelines.

Sustainability and Environmental Impact:

- Develop robust sustainability assessment frameworks tailored to DfMA-built structures;

- Incorporate circular economy principles into DfMA practices.

Regulatory and Policy Consideration:

- Focus on the development of regulatory and policy frameworks for implementing the DfMA methodology;
- Explore potential synergies between Integrated Project Delivery (IPD) and construction-oriented DfMA.

Collaborative Approach:

- Delve into the complexities of different collaborative approaches in DfMA through in-depth case studies;
- Develop practical strategies and frameworks for the establishment and maintenance of collaborative information-sharing systems;
- Systematically integrate collaborative approaches into BIM workflows for enhanced project assessments in DfMA.

Application, Benefits, and Challenges:

- Conduct comprehensive validation studies of the DfMA scoring tool using real case studies;
- Explore diverse application scenarios of DfMA in different construction settings and building types;
- Analyze contextual factors influencing the success and challenges of DfMA in diverse construction contexts.

Project Lifecycle:

- Prioritize a holistic examination of DfMA principles across different project lifecycle stages;
- Expand the exploration of DfMA-oriented design beyond pre-fabrication;
- Foster environmentally conscious construction practices through a comprehensive understanding of DfMA's potential impact across the project lifecycle.

These recommendations cover a wide range of areas for future research, offering valuable insights that will further advance the understanding and application of DfMA in the construction industry.

Author Contributions: S.M. contributed to the conceptualization, methodology, software development, formal analysis, investigation, resource management, data curation, writing of the original draft, and visualization of this research. Z.L. provided supervision throughout the project. N.O. played a pivotal role as the project manager, contributing to validation, data curation, writing—review and editing, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Sciences and Engineering Research Council of Canada Alliance Grants, grant number ALLRP 586339-23.

Data Availability Statement: No new data was created in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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