Generative Design for Prefabricated Structures using BIM and IoT applications – Approaches and Requirements

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Abstract –

Building Information Modeling (BIM) has demonstrated a wide range of merits over traditional and modern constructions. The integration of generative design (GD) with BIM in the construction industry has become an interesting topic, even though the concept is not very new. Prefabricated construction (PC) offers several advantages over traditional construction and has recently advanced to a new level of study because of the usage of BIM. The synchronization of BIM with PC is becoming simpler to create automatic design solutions in its early phases, thanks to the current breakthroughs in the internet of things (IoT) and its applications. There has been an increase in research interests that are mostly focused on examining tools and applications. However, there are not many studies that have looked at methodological relationships and other factors, which has led researchers to focus more on GD-BIM-based investigations. This study provides a preliminary critical analysis of the software, skill, and methodological requirements for current GD-BIM integration methodologies. The publications are pulled from web of science platform and thoroughly examined in statistical and systematic methods to give a fresh viewpoint on objective-oriented and skill-driven GD-BIM development for PC. New guidance to improve skill learning for GD-BIM development is recommended in this study. The analysis and recommendations might aid the researchers and designers in comprehending the situation and paying attention to future requirements.

Keywords –

Generative Design, Building Information Modeling (BIM), Prefabricated Construction, IoT Applications.

1 Introduction

Prefabricated Construction (PC), a technologically advanced construction method, is regarded as the first step toward industrialization in the construction industry following mechanization, automatic control, and production [1]. PC has merits over conventional construction methods, including the ability to build more quickly and cheaply, with better quality control, and with less material waste. PC promotes sustainability, and it has been the main concern in all engineering fields. Even though PCs have many benefits, adoption is hampered by factors like expensive design costs, significant capital expenditures, a lack of supply chain data, etc. [2]. Building Information Modeling (BIM) is frequently used as a potential solution to the sector's long-standing problems in architecture, engineering, and construction (AEC) [3]. Although Generative Design (GD) has been developed in the 1970s, it is currently integrated into BIM to increase its benefits for the building industry. The growing trend for GD-BIM integration can enhance BIM's ability to produce a wide range of design possibilities, which can lower the cost of PC design and also other hindrances [4-7].

GD-BIM integration in traditional construction has been attempted by several studies, but in PC, it has been found to be limited and there is no clear information on this. For example, some GD-BIM are produced and investigated to effectively address design difficulties, while other research examines software and programming techniques to compare developing tools [8-10]. To understand the methodological connection, skill requirements, and improvements to help designers, this study seeks to evaluate the present methods of GD-BIM in PC. To find the answer, the Web of Science (WoS) platform is used to search for publications relevant to this goal and conduct extensive analyses of those articles. The sections are organized as follows: GD-BIM integration, Methodology, Analysis & Discussions, and Conclusions & Recommendations. This study can provide comprehensive information regarding the adoption of GD-BIM in PC at this time.

2 GD-BIM integration

This section examines background information on

GD, its components, BIM, and GD-BIM integration to illustrate the need for and reasoning behind building GD in BIM.

2.1 Generative Design Elements

Generative design is a type of iterative design process. Using software and computational algorithms, generative design is a goal-oriented and simulation-driven design process that creates high-performance geometry based on user-defined technical requirements. Simply described, "GD systems" are systems that try to assist professional designers and/or automate portions of the design process using computational approaches [11]. Krish describes the GD components into three as follows: (1) “a design schema”, (2) “a means of creating variations”, and (3) “a means of selecting desirable outcomes” [12]. Marsh explains that GD requires three elements that are (1) “performance metric”, (2) “configuration variation”, and (3) “decision-making response” [13]. These studies help us to summarize the GD as three major elements in familiar terms, that are:

(1) Parametric design (Generate);
(2) Simulation (Evaluate); and
(3) Optimization (Evolve).

GD development often follows several steps that are depending on the requirements of the problem. Among these, the algorithm development and the design goals/constraints setup constitute the key phase from which the parametric models are derived. Here, GD is decomposed into two major steps (1) algorithm and (2) design constraints.

2.1.1 Algorithm

An algorithm is a set of rules that a computer must follow to execute computations, carry out other problem-solving tasks, or create and optimize various models. Singh and Gu examined and outlined the most popular architectural design algorithms, which include cellular automata, genetic algorithms, L-systems, shape grammars, and swarm intelligence [11]. In terms of applications, the right algorithm selection is made based on the characteristics of the design goals. For instance, the Shape Grammars technique is probably chosen if the design goals are to haphazardly discover space arrangement or visual compositions. Alternatively, the genetic algorithm is typically used if the goal is design optimization or improvement.

2.1.2 Design Constraints

The design goals or constraints are related to scope of the projects. The same design objectives or limitations cannot be applied to every building project. For example, some projects might concentrate on design generations and optimization, others might concentrate on lighting and ventilation, still others might concentrate on reducing embodied emissions, etc. The design constraints are a set of design criteria or motivations, such as dimensions restrictions, material choices, manufacturing processes, or even financial restrictions, etc. [14, 15]. At present, designers detail their design objectives in programming languages, and automated script development research is slowly growing, but there is still a long way to go. Figure 1 shows a basic flowchart of the generative design process.

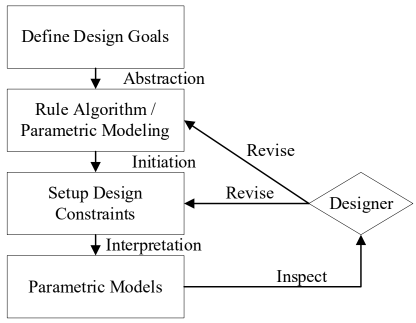

Figure 1 Generative Design Procedure

2.2 BIM in PC

BIM may assist PC in a variety of ways. BIM enables more precise material specification, which can lower over ordering and hence lower waste on the construction site. Fabricators and contractors can benefit from BIM by getting a 3D model of the element positions. To support building maintenance, subsequent demolition, and material recycling at the building's end of life, BIM can also store building information. When used wisely, BIM technologies can precisely describe the geometry, behavior, and characteristics of individual building components and objects, making it easier to incorporate them into standardized architectural parts or digitally accessible volumes [3].

BIM have shown greater improvements in design stage, cost calculations, supply chain and logistics and waste reduction in PC [1, 2, 5]. Currently various BIM software are available like Autodesk Revit, Tekla Structures, Graphisoft ArchiCAD, Bentley Microstation, Autodesk BIM 360 etc., that can be adopted based on the project requirements. It is more than just software because it makes it possible for all its users to manipulate and maintain shared data and information resources.

2.3 GD-BIM Integration

Although the implementation of BIM in PC has been widely discussed, most of it focuses largely on its later stages like fabrication, waste reduction, installation safety, supply chain and logistics. The BIM usage at the early stages like design development, structural design, MEP design are relatively less in PC. The main hindrance is its inadequacy of capabilities, thus the integration of IoT applications like generative design, parametric modeling can enhance its implementation [16].

As a computer-aided design, geometric modeling is the focus of the GD to provide quicker design possibilities, but it is unable to preserve building information. As opposed to BIM, which allows for PC design with geometry and stores its information, design variants take longer to complete. Therefore, using this IoT method with well-known BIM software can increase PC use. Software like Revit currently supports Application Programming Interface (API), which enables users to add-on plugins and create their own tools through programming to optimize workflows.

3 Methodology

To remove the skewed conclusions, the review process uses a mixed review methodology that combines quantitative analysis and qualitative investigation. Since the Web of Science (WoS) database's rigorous peer review procedure sets a standard for published publications, it was chosen as the platform for article searching. For quantitative analysis, widely accepted VOSviewer software is used that can visualize the contemporary research status whereas the qualitative discussions focus on the objectives of GD-BIM implementation in PC and the relationship to the programming language, and skill requirements and learning paths of programming languages for GD-BIM development in PC.

GD is often related with Parametric Design (PD), Algorithm Design (AD) and geometric modeling, so all these terms including BIM, AI and IoT are used as initial keywords. The initial search generated 966 results but most of the papers focuses on conventional methods and out of the scope.

For precise results, the inputs are revised as *"geometric modeling*" or "parametric design" or "generative design" or "algorithm design" or "DFMA" or "parametric modeling*" or "Design algorithm" or "algorithm" (Topic) AND "BIM" or "Building Information Model" or "Building Information Modeling" or "AI" or "artificial intelligence" or "IoT" or "Internet of Things" (Topic) AND "prefabrication" or "prefabricated buildings" or "prefabricated structures" or "prefabricated construction" or "modular Construction" or "precast construction" or "offsite construction" or "modular integrated construction" or "ppvc" (Topic) and Engineering Civil or Construction Building Technology (Web of Science Categories)* produced 33 findings demonstrating the GD-BIM application in PC is in its initial phases. Figure 2 shows the flowchart for methodology adopted in this study.

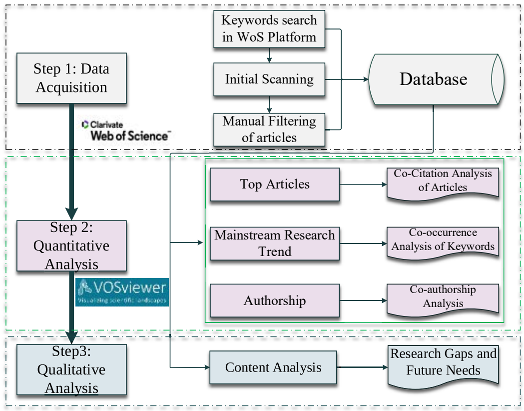

Figure 2 Methodology – Flowchart

4 Analysis and Discussions

As stated in the methodology section, the analysis of the retrieved materials is divided into two primary categories: quantitative and qualitative approach. The former study validates itself using numerical data, whereas the latter one offers more subjective conclusions.

4.1 Quantitative Analysis

To grasp the dominant research trends, top papers, and influential authors, the bibliometric software VOSviewer is used to analyze co-occurrence of keyword, article citations and journal citations which provide a quantifiable perspective of the subject area. The WoS platform's number of publications and the citations over the years is represented visually in Figure 3, which indicates that the GD-BIM implementation in PC took place in 2006 with one article but there is no article found in the successive years until 2011. Although articles scattered in 2012 and 2014 but there is no consistency in the publications. Notably, the number of publications and citations increased from 2018 until 2022 with 9 publications and 239 citations, describing that the subject's importance.

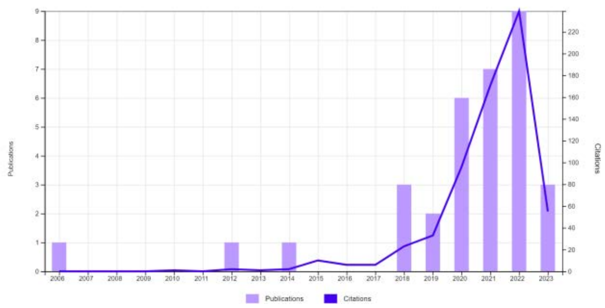

Figure 3 Year-wise publications in WoS

As illustrated in Figure 4, there are 30 original research publications and 3 review articles among the published works, demonstrating the researchers' greater interest in understanding the subject matter.

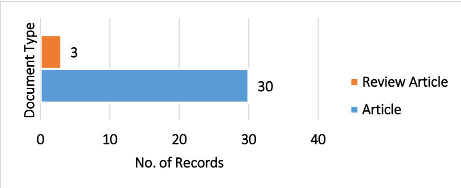

Figure 4 Type of published documents.

4.1.1 Co-occurrence of Keywords Analysis

The primary subject matter of published documents is represented by keywords, which also highlight the breadth of subject matter covered within any given domain. To illustrate the findings of the bibliometric analysis of the literature, the network of keywords was visualized. In the generated distance-based map, a greater distance often denotes a weaker association between the two objects. The size of the item label reflects the number of publications where the keyword was discovered, and the varied colors indicate the various knowledge domains that were grouped together using the clustering technique.

Since there are 33 publications, and Figure 3 clearly shows that the study area is in its early stages, the minimal number of occurrences was set to 2, making 47 of the 224 keywords meet the threshold. The network of related keywords is depicted in Figure 5 with 47 nodes, 360 linkages, and a total link strength of 84.50. The keyword occurrences and node strengths are summarized in Table 1.

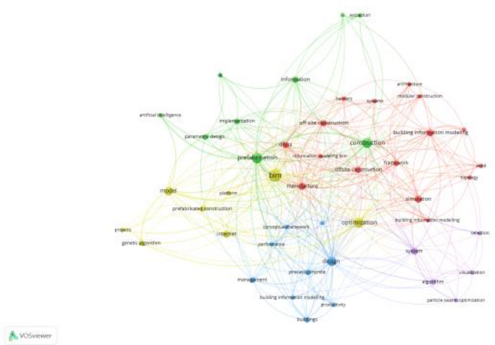

Figure 5 Bibliometric Network of keywords

According to Table 1, "BIM" including its abbreviation is the most frequently occurring keyword (24 times), with 83 links containing other keywords and a total link strength of 23. The successive keywords “prefabrication” & “construction” are found to be common with link strength as 10 & 9 respectively. The specific keywords like “optimization”, “model”, “internet” and “simulation” occurred more than 5 times with atleast 20 links with the other keywords and the reasonable link strength clarifies that the authors pay more importance in applying the IoT applications in their research. With minimum of 3 occurrences, the keywords such as "generative design", “algorithm”, “parametric design” and “artificial intelligence” clearly supports the argument that the research area is in its inception level.

Table 1 List of top 10 keywords mapped

Keyword	Occurrences	Links	Total link strength
building information modeling (bim)	24	83	23
prefabrication	10	31	10
construction	9	31	9
optimization	9	30	9
design	8	30	8
model	7	20	7
internet	5	21	4
manufacture	5	26	5
simulation	5	20	4
dfma	4	24	4

4.1.2 Citation Analysis of Articles

By measuring the number of times that author, article, or publication has been cited by other people, citation analysis is a typical method for determining the relative relevance or impact of an author, an article, or a publication. It is a crucial tool for any literature study and aids researchers in determining how frequently a work has been cited in articles. Citation analysis is considered since the research field is in emerging stage that is more meaningful in understanding the most research contributions by the authors. VOSviewer generated citation network is shown in Figure 6 and Table 2 lists the top 7 documents with minimum of 25 citations and their links. The threshold is set up as minimum 3 citations that generated the network between 24 documents out of 33 as represented in Figure 6.

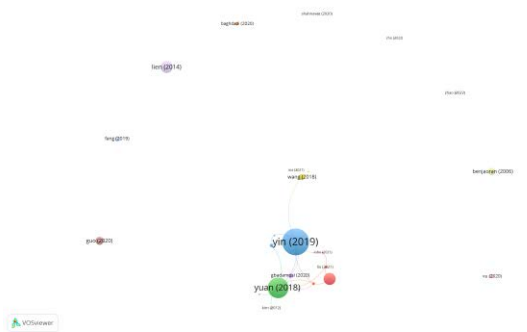

Figure 6 Document Citation Analysis Network

From the Table 2, Yin et al. (2019) [17] published a systematic review article cited 149 times followed by the article focusing on DFMA published by Yuan et al. (2018) [18] cited 110 times and the article which focus on optimizing tower crane layout by Lien and Cheng (2014) [19] cited by 60 articles. Interestingly, the Figure 6 clearly shows there are 9 articles that has citations but there is no connection with the others which directly represents the status the research topic as its initial level.

Table 2 Top 7 Cited Documents

Document	Citations	Links
Yin (2019) et al [17]	149	7
Yuan (2018) et al [18]	110	8
Lien & Cheng (2014) [19]	60	0
Banihashemi et al (2018) [20]	59	2
Guo et al (2020) [21]	37	0
Benjaoran et al (2006) [22]	33	0
Wang et al (2018) [23]	28	3

4.1.3 Citation Analysis of Journals

Journal citation analysis is carried out to understand the overall idea about the publications which pays interest in this research area. Interestingly there are only 11 journals found with the Automation in Construction holds maximum of 15 articles which is 45.5% of the total, Buildings and Journal of Construction Engineering and Management holds 15% & 9% with 5 & 3 articles respectively. The remaining 30% is shared by the other 8 journals. This indicates that most of the author intends to publish in journals with a high impact score.

Figure 7 shows the citation network of sources developed for a threshold of minimum 1 journal and 10 citations, which resulted 7 out of 11 journal sources. Table 3 lists the top 5 resulted journals and their respective number of articles and citation count.

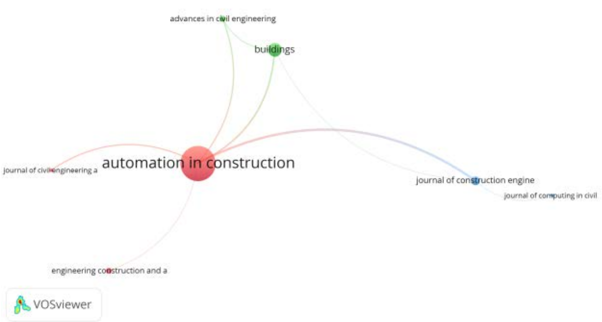

Figure 7 Journal Citation Network Analysis

Table 3 Top 5 List of Journals and their Citations

Journal Name	Articles	Citations
Automation in Construction	15	533
Buildings	5	11
Journal of Construction Engineering and Management	3	10
Engineering Construction and Architectural Management	2	24
Advances in Civil Engineering	2	13

4.2 Qualitative Analysis

This section examines the methodological linkages between the GD-BIM development objectives in PC, the applicability of programming languages, and the learning and development of programming abilities. Therefore, viewpoints of objective-oriented, and skill-driven GD-BIM adoption in PC are presented. The Co-occurrence of keywords analysis generated 5 clusters with 47 keywords as shown in Figure 5 is for subjective analysis to unfold more about the approaches and requirements.

4.2.1 Objective Oriented GD-BIM in PC

The two major objective of GD-BIM integration in PC are (1) solve specific design tasks and (2) support design process. While supporting design tasks are primarily used by researchers to enhance the overall design capabilities that are common to all projects, solving specific design tasks is typically project-based and is primarily developed by practitioners with the aim of solving individual design tasks creatively and efficiently. For instance Banihashemi et al. integrated parametric modeling PC to reduce construction waste using genetic algorithm through Rhinoceros 3D–Grasshopper platform resulted by 2% improvement [20]. Liu et al. used Simphony NET 4.6 to develop a simulation model in the Autodesk Revit software by inheriting its API in order to automatically generate the panelization design of manufacturing components [24]. In order to determine the best layout for PC drywall installation planning, Lobo et al. designed a framework with a decision support module that takes into account environmental, economic, and aesthetic factors [25]. This framework has shown to be beneficial. They used heuristic optimization algorithms and simulation-based design algorithms to choose the ideal.

Bakhshi et al. [26] used the framework proposed by Yuan et al. for supporting client engagement within offsite construction using Dynamo plugin in Revit software [18]. In order to restore the physical characteristics of PC components and support its informatics, Xu et al. reverse-modeled a PC component in Industry Foundation Class (IFC) using the equal-interval segmentation slice mapping approach [27].

Rest of the articles focuses on GD-BIM integration in

PC to support design process. For instance, Yuan et al. proposed a framework for Manufacture and Assembly Design (DFMA) [18], which is an organic combination of DFM and DFA. This framework instructs designers to fully consider the requirements from manufacture and assembly of PC at the design for better manufacturability and assemblability using Split design and DFMA analysis.

Similarly Bai et al. developed a common library for PC structural components using Graphic Media Mapping and EXPRESS language that can be used in Java tools [28]. Gan developed a graph data model and BIM-based geometric modeling in PC to support the overall design capabilities [29, 30]. In contrast to Textual Programming Languages (TPL) like Python, C#, or Java, Visual Programming Languages (VPL) like Dynamo and Grasshopper are easier to adopt and mimic the needs in.

4.2.2 Skill-driven GD-BIM adoption in PC

VPLs are simple to learn and use because they were created to facilitate simple computer interaction and were later used as teaching resources to train beginning programmers. TPLs are far more challenging to master, but once properly coded, they are capable of handling complex problems.

A user who is fluent in one TPL can design GD in several BIM environments using Rosetta/ HP ARIES without having to learn additional new programming languages. Rosetta serves as a conduit or converter, enabling users to program GD using specific TPLs (as front-end languages) and produce similar GD models across various applications (as back-end environments). Based on a thorough examination, designers at the entry level can utilize VPLs like Dynamo for Revit and Grasshopper for Rhino with ease due to their strong support for intuitive and novice users. Ma et el. suggested a path for skill development to improve GD-BIM integration based on the review process but it was not well described [31]. Thus, a modified new guidance to excel in GD-BIM integration for a newbie designer is shown in Figure 8, the same can be adopted for GD-BIM integration in PC. Consequently, to generate GD-BIM for simple designs, the designers must have at least a basic understanding of one programming language (either a VPL or TPL), but it is advised that they have a solid understanding of at least one TPL as well as AI approaches in order to build complicated designs and models.

GD is a process of using algorithms and computational tools to generate multiple design options that meet specific design criteria. Researchers are adopting various TPLs like Python [32], C#, JavaScript, Visual Basic based on their knowledge skills and requirements. Among which python is most widely used and easy to learn/use than other programming languages. Regarding the algorithms, generative adversarial network (GAN) [33], genetic algorithm [34], particle swam algorithm [19], random forest [32] with TPLs that effectively improved the efficiency of generating large set of design variations and optimizes it to provide the best suited one for the design goals and constraints. The application of AI algorithms may aid in data analysis, problem solving for design challenges, predictive modeling, timetables and reporting, among other complicated tasks in the PC sector, in addition to design simulations and optimization. Although it is claimed that the complexity of the joints and connections in the PC design results in minimal variations, the integration of GD-BIM in the PC might be able to overcome this obstacle.

Thus, the selection of VPL/TPL and algorithms can be made based on the designers' skillset and the problem to be addressed. Ergo, the IoT and artificial intelligence technologies of today could greatly assist the designer in creating a variety of design solutions that take sustainability into account.

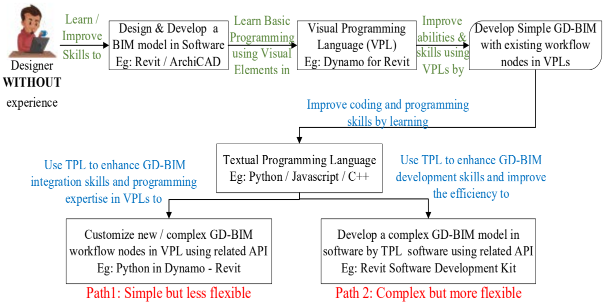

Figure 8 Guidance to improve skill learning for GD-BIM development

5 Conclusions and Recommendations

This section concludes the findings and offers suggestions for further research in the field based on the analysis and discussion of this study.

5.1 Conclusions

The main goal of this study is to review statistically and descriptively the status of GD-BIM integration in PC. This study has made it very evident what skills are needed to accomplish goal-oriented GD-BIM integration. Consequently, it is evident that the use of GD-BIM in PC is still in its infancy and that very few authors have made an effort to investigate it. The creation of generative design using BIM for PC can be made possible because of developments in AI and IoT applications. As a result, one obstacle, such as expensive design costs for design options, can be addressed. The employment of GD-BIM in PC research has produced effective results, and the strategy for achieving its integration has improved, according to the conclusions of all the articles.

It is also observed that, like the development of GD-BIM in conventional construction design, only a small number of authors implemented the integration for specific problems, with the majority focusing on general design improvements. Additionally, it should be emphasized that the research topic does not examine many of the issues that must be considered during the early design stages, including spatial requirements, lighting and ventilation, MEP systems, quantity take-off, cost calculations, and more. In terms of the programming and skill needs, the designer or researcher should firmly hold at least one competence in either VPL like Dynamo, Grasshopper, Solibri Model Checker (SMC) or TPL like Python, C#, C++, or Java. The VPL/TPL can be interacted with 3D model BIM applications like Revit, ArchiCAD, and Tekla through its API. With the development of computing technologies like machine learning (ML), artificial neural networks (ANN), GAN, and various algorithms, including but not limited to genetic algorithms, evolutionary algorithms, and swarm algorithms, the potential for this research field is enormous in the current decade.

5.2 Limitations and Recommendations

Following a thorough examination, certain recommendations are made that might be very helpful for designers and researchers as they develop and apply generative design principles to the prefabricated construction technique. They are as follows:

1. Although GD have been tested for traditional construction methods while taking numerous elements into account, the same cannot be employed for PCs because of the different design process.
2. A strong potential to work either with VPL or TPL to effectively blend GD with BIM in PC.
3. The study theme is still in its early phases and has the potential to be explored in a variety of ways, as it is mentioned earlier.
4. By generating different design choices and optimizing them, GD, which focuses on early design stages, has the potential to reduce waste reduction and carbon emission while maximizing the PC benefits.
5. A GD framework that incorporates all design criteria can be created using BIM in PC and that can be used for every project.
6. To accommodate additional design processes, more sophisticated and organized GD-BIM could be developed.
7. It's indeed possible to conduct multidisciplinary research to ease the programming challenges.

This analysis on the approaches and requirements on GD-BIM integration in PC can help the researchers/ designers to understand and explore more on it. The study is an overview of the subject and also limited to the WoS database which covers the scholarly articles only rather than the conference and other sources.

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