A Bibliometric Analysis of Generative Design, Algorithmic Design, and Parametric Design in Architecture

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ABSTRACT

This research aims to display, compare, and analyze the keywords related to parametric design, generative design, and algorithmic design. Digital design has become increasingly inseparable from architects; thus, 3D modeling software has become a necessity for architects. The digital workflow has put computational design—generative design, algorithmic design, and parametric design—into importance. There are emerging trends for the past decade, and a bibliometric analysis can display information about trends in the literature. Literature trends may provide insight into the direction of computational design development. This study uses a bibliometric analysis with VOSviewer and data from Lens to identify the trends from 2011 to 2021. The result indicates several trends: artificial intelligence, computation, machine learning, visualization, and internet technology. The trend analysis needs to be continued in other computational design categories to find continuity in the findings.

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1 INTRODUCTION

Technological advancement has made digital architecture possible. Unlike most architectural styles of the late 20th century that emerged from a theoretical purpose, digital architecture has rationalized its position in architectural discourse and has sought to free the architectural design discipline from linguistic and representational criticism [1]. Computers provide tools to enhance individual abilities, one of which is architecture. As time goes by, the use of architectural software is increasing. The assimilation of digital processes and architecture created digital architecture [2], and it leads to computational thinking and computational design to be relevant in architecture. Computational thinking is a way of devising computational resolutions to solve problems [3]. It serves as a foundation for computational design.

Computational design is the method of employing programming to design and alter forms and structures [4]. There are three categories of computational design: algorithmic design, generative design, and parametric design. We can trace "parametric design" appeared in 1971, as Moretti defined the term [5]. Then, "generative design" emerged in 1975 in research by Mitchell [6]. In 2003, "algorithmic design" appeared in a publication by Terzidis [7]. Parametric design is a method of parametric model creation based on particular variables: dimensions, quantities, or geometries [8]. Generative design is a design exploration method to produce optimum designs by employing topology optimization while facing several limitations [9]. Algorithmic design is a design procedure that utilizes algorithms: Visual Programming Language (VPL) and Textual Programming Language (TPL) [10]. Both generative design and algorithmic design uses algorithms. The difference is that algorithmic design is more specific in utilizing them to achieve outcomes [11]. The parametric design utilizes parameters. There are differences between algorithm and parametric. An algorithm is a set of mathematical instructions that will help calculate an answer to a problem [12]. Meanwhile, a parameter is a collection of a fixed limit that organizes or restricts how something can be done [13].

Each computational design category has a variety of implementations. There are various applications of algorithmic design in architecture, including 3D printing at building scale [14] or creating structurally feasible façades [15] and residential housing [16]. Meanwhile, the generative design also has several usages: design exploration of various shapes [17], form-finding by using sound [18], performance-based urban form design [19], occupancy congestion prediction [20], decorative architectural parts [21], generating floorplans [22], and BIM automation [23]. There are ecological applications of generative design, such as decreasing unnecessary construction waste [24], minimizing greenhouse gas emissions from materials [25], and energy performance optimization [26]. Generative design is also beneficial in the production stage: mass-customization [27] and mass-production [28]. In the meantime, parametric design has various applications in architecture: conservation [29], restoration [30], urbanism [31], landscape planning [32], green building [33], wind-based design [34], prefabricated buildings [35], wooden structures [36], design exploration [37], emulate patterns [38], analyzing performance [39], building structure analyses [40], visual comfort [41], and BIM [8]. It can also help to create less ecological damages: structural efficiency [42], sustainable building renovation [43], daylighting [44], and energy-efficient building form [45].

There have been several applications of algorithmic design, generative design, and parametric design in practice. Chen applied algorithmic design principles for generating housing layouts [16]. They created an algorithmic model to divide an area into different sizes and categories (public, private, and buffer zones). They visualized the model with the algorithm using Rhinoceros 3D and Grasshopper.

Khan et al. applied generative design for exploring various design shapes [17]. In the beginning, they established geometric parameters of a CAD model by also considering psycho-physical design metrics. Then, they generated design alternatives with Euclidean distance-based Sampling Teaching-Learning-Based Optimization (S-TLBO). The result was varying furniture designs from a single CAD file. Meanwhile, Cruz implemented a parametric design to reconstruct the dome in the Ex-Oratory San Filippo de Neri [30]. There were determined geometric parameters to emulate the dome design with Rhinoceros 3D and Grasshopper.

There have been rising trends in computational design for the last ten years. While there are comparisons of computational design methods [46] and implementations [14], [15], [24], [25], [31], [32], analyzing trends based on bibliometric analysis can reveal insights into the direction of computational design advancement based on literature trends. This study aims to identify, analyze, compare, and explain the development of computational design—generative design, algorithmic design, and parametric design—in literature to answer several questions: why some trends endure in some areas and what paths the development will advance. The conclusion then correlates the occurring keywords with further significant implementations from computational design.

2 RESEARCH METHOD

The research used bibliometric analysis, which is a procedure to present a perceptible summary of massive quantities of scholarly research [47]. It began with exporting search data from Lens then analyzing them with VOSviewer to identify co-occurrence of keywords. Lens displayed web search data for scholarly works. VOSviewer generated visual maps of web search data from Lens to analyze trends in scientific research. Examining trends need data from a range of years; thus, the search obtained Lens data in ten years (from 2011 to 2021): generative design in architecture, algorithmic design in architecture, and parametric design in architecture. The keywords from each search were analyzed and compared to discuss the trends—the conclusion related the occurring keywords with more consequential applications from computational design.

3 RESULTS AND DISCUSSION

The research obtains data from Lens. There are 6,467 scholarly works in Generative Design in Architecture, 68,441 in Algorithmic Design in Architecture, and 13,772 in Parametric Design in Architecture. VOSviewer then generates the overlay visualization of keywords co-occurrence from the search data (Figure 1, Figure 2, and Figure 3).

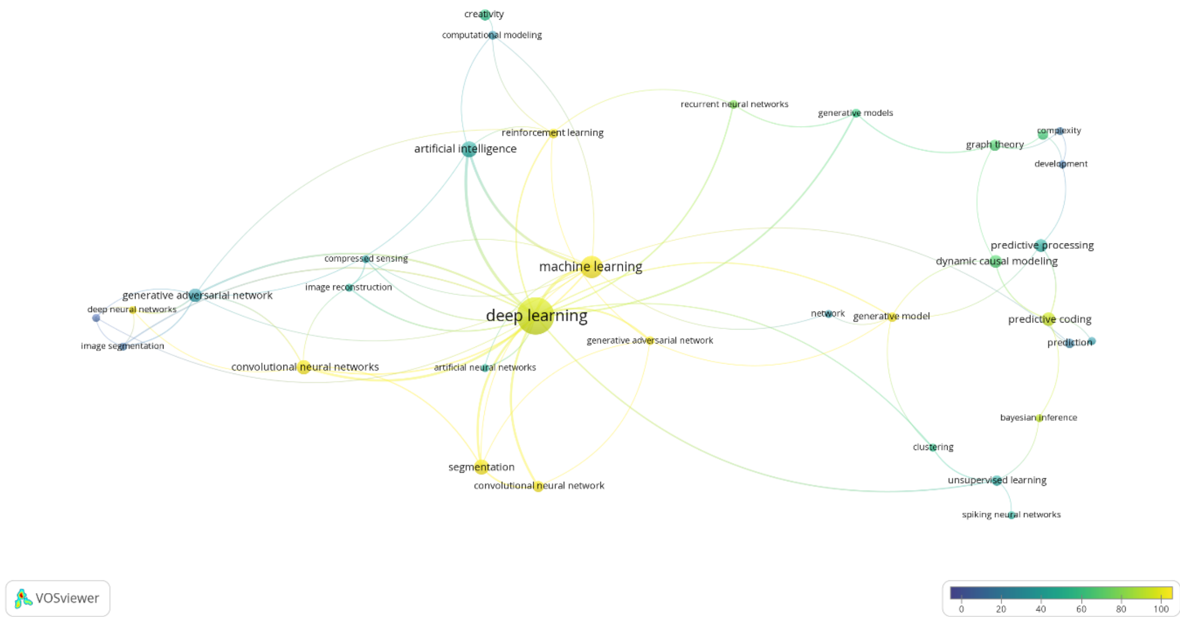

Figure 1. The average citation of generative design in architecture

Figure 1 shows the overlay visualization of the average citation of generative design in architecture. The most cited keywords related to architecture with the most network are machine learning, deep learning, artificial intelligence, convolutional neural network, reinforcement learning, and generative adversarial network.

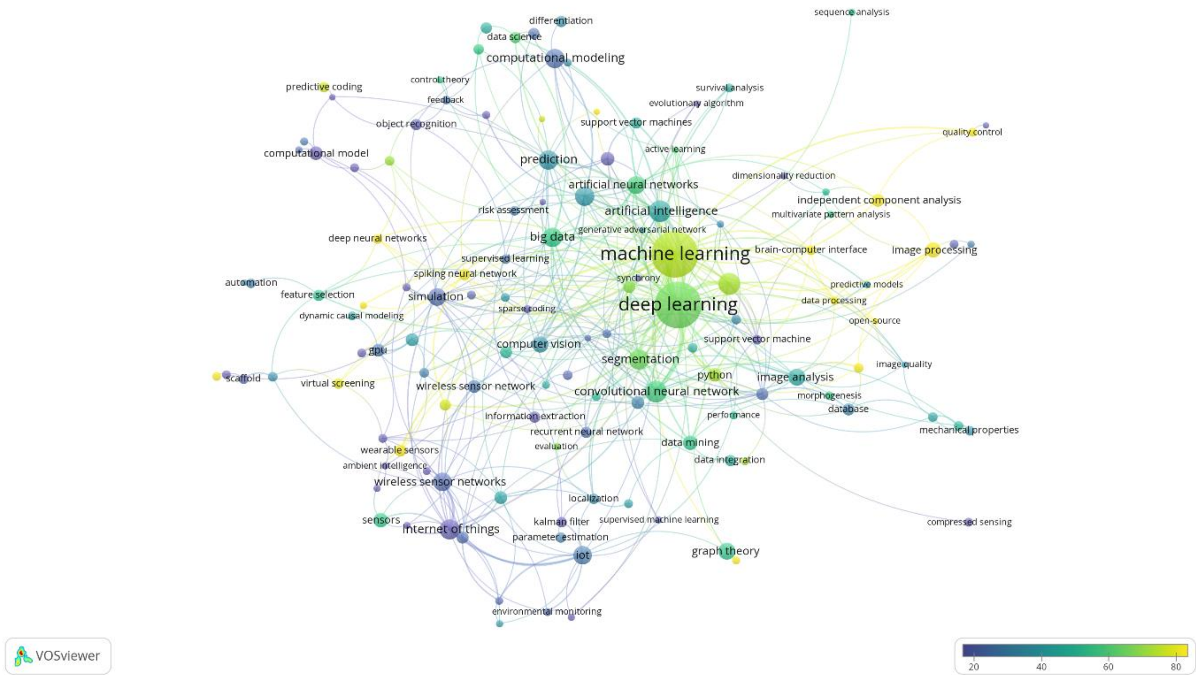

Figure 2. The average citation of algorithmic design in architecture

Figure 2 shows the overlay visualization of the average citation of algorithmic design in architecture. The most cited keywords related to architecture with the most network are machine learning, deep learning, artificial intelligence, convolutional neural network, and computational modeling.

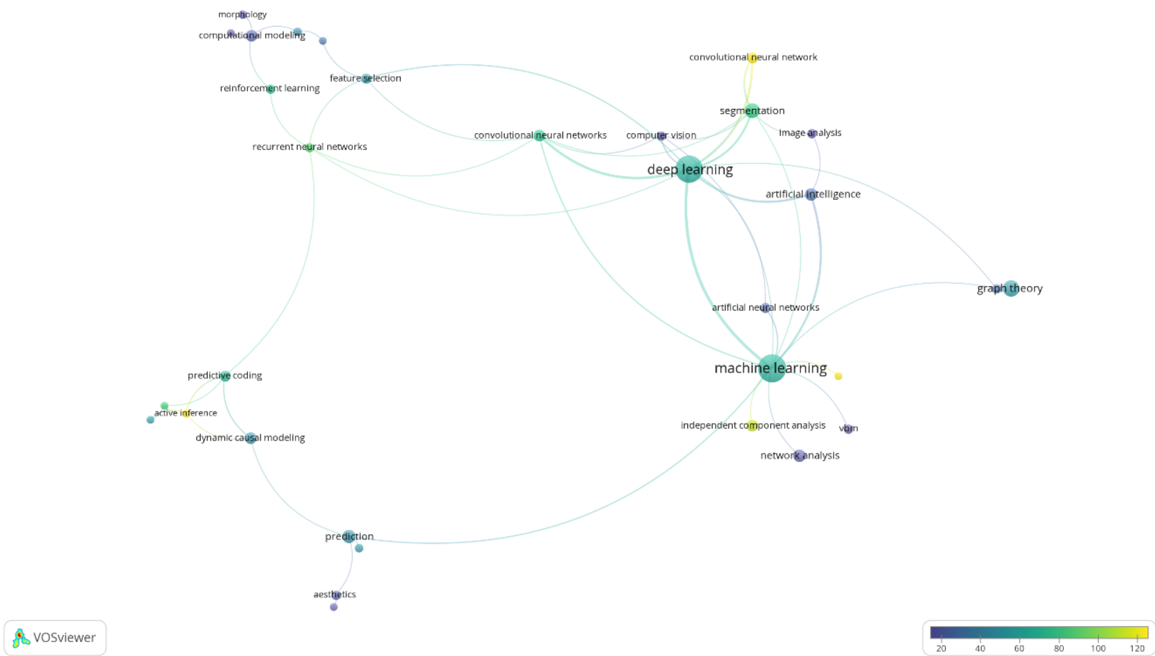

Figure 3. The average citation of parametric design in architecture

Figure 3 shows the overlay visualization of the average citation of parametric design in architecture. The most cited keywords related to architecture with the most network are machine learning, deep learning, artificial intelligence, and convolutional neural network. Primary keywords constantly appear in all three search data: artificial intelligence, artificial neural network, computational modeling, convolutional neural network, graph theory, machine learning, recurrent neural network, and reinforcement learning.

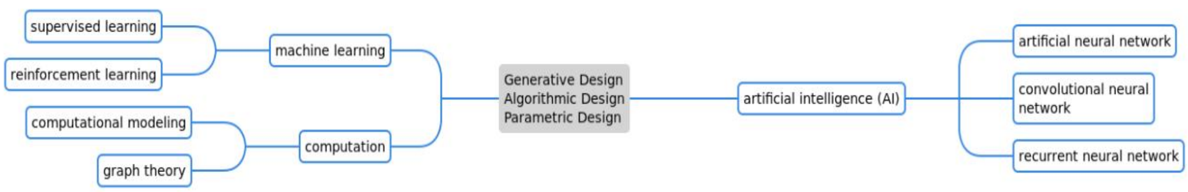

Figure 4. The re-occurring keywords

Some keywords are closely related to one another and form groups (Figure 4). One group constitutes artificial intelligence technology: artificial neural network, convolutional neural network, and recurrent neural network. Artificial intelligence (AI) is a computer science technology that performs tasks efficiently and ethically with algorithms [48]. The artificial neural network (ANN) is a computing operation that imitates the brains' cell system [49]. Meanwhile, the convolutional neural network uses a backpropagation algorithm for identifying spatial hierarchies [50]. The recurrent neural network uses safe indicator sensors to assess conditions [51], enhance precision [52], and foretell the coming words [53]. Meanwhile, the co-occurrence of these keywords displays a significant role of AI in these computational design categories. AI aids designers to add specific functions to produce their design accurately with identifying correct algorithms in generative & algorithmic design and parameters in parametric design.

Other keywords discuss machine learning consisting of supervised learning and reinforcement learning (Figure 4). Machine learning is a domain of computer science that permits computers to learn without explicitly programmed and resolve certain obstacles [54]. Meanwhile, supervised learning is a part of machine learning in which it detects and links data based on examples [55]. Reinforcement learning is an unsupervised learning approach of interact-feedback (trial-and-error) in real-time [56] to adapt procedures for decision-making difficulties [57]. Machine learning also aids designers in accurately designing their projects by identifying and implementing correct algorithms and parameters.

Meanwhile, there are keywords related to computation: computational modeling and graph theory (Figure 4). Computational modeling is a virtual workroom [58] that allows users to revise various prospects and examine chosen scenarios [59]. Graph theory is an efficient modeling, analysis, and computational method [60] for a broad spectrum of connected systems [61]. Computation is apparent in generative design, algorithmic design, and parametric design because it is the way algorithms and parameters are encoded to be readable by computers while applied in software.

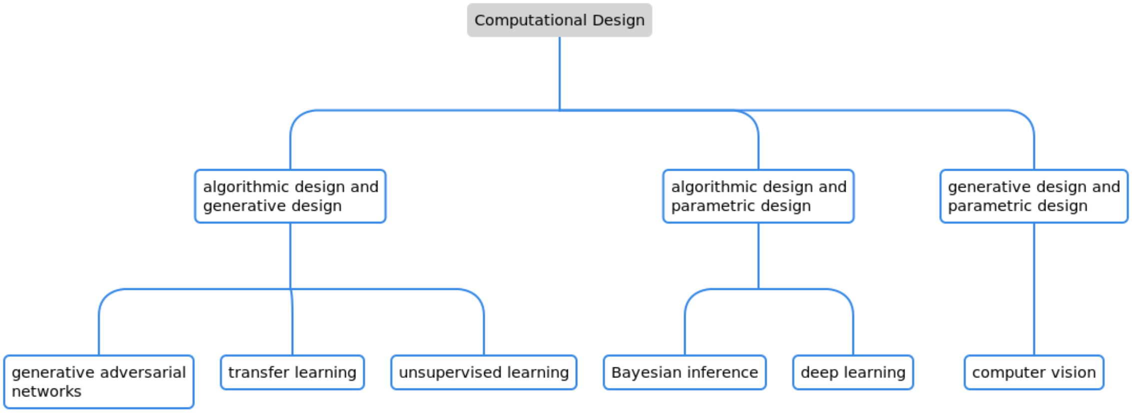

Figure 5. The re-occurring keywords in related to each computational design

Meanwhile, there are keywords in different computational design categories (Figure 5). Three keywords appear in the algorithmic and generative design: generative adversarial networks, transfer learning, and unsupervised learning. Two keywords (Bayesian inference and deep learning) appear in generative and parametric designs. One keyword, computer vision, appears in algorithmic design and parametric design. The re-occurring keywords display the relationship with each computational design category. Algorithmic design and generative design are closely related to others. Moreover, the re-occurring keywords can generally be applied to others under the computational criteria.

The generative adversarial network (GAN) appears in algorithmic design and generative design (Figure 5). It is a model that consists of generator and discriminator networks [62]. Generator networks produce images, and discriminator networks select ideal images to form expected data [63]. The technology can generate detailed pictures with just simple strokes. The algorithm in algorithmic design and generative design can apply GAN.

Transfer learning also appears in algorithmic and generative designs (Figure 5). It is a means of reusing a previously implanted model knowledge for different tasks to classify and regress data [64]. This mechanism allows the design to be more precise according to the designers' needs by basing the algorithm on another model knowledge. Moreover, algorithmic and generative design algorithms provide a possible way to do it.

Unsupervised learning also appears in algorithmic and generative designs (Figure 5). It is a way of educating algorithms to detect unknown structures in unlabeled data [65] by employing unclassified and unlabeled information and enabling it to operate without supervision [66]. In addition, the mechanism is helpful to decrease designers' involvement in managing some algorithms and data; thus, decluttering some processes.

Meanwhile, Bayesian inference occurs in generative and parametric designs (Figure 5). It is a manner of limiting hypotheses, so the remaining ones can accurately interpret data [67] by replacing previous information based on observational data [68]. Furthermore, it eases the computational analyses by reducing unnecessary processes. Generative and parametric designs can have various algorithms and parameters according to designers' needs, and Bayesian inference helps compute efficiently.

Deep learning also appears in generative and parametric designs (Figure 5). It is a collection of machine learning procedures that apply multilayered neural networks to analyze signals or data automatically [69]; thus, it is the most efficient, controlled, time-efficient, and cost-efficient machine learning method [70]. Moreover, the procedure helps to find data and generate more detailed designs using algorithms in generative design and parameters in parametric design.

Meanwhile, computer vision appears in algorithmic and parametric designs (Figure 5). It is a field that encompasses features of pictures and videos processing, which artificial visual systems implement for programmed scene examination, presentation, and perception [71]. Computer vision helps designers examine visual data for computational processes while creating algorithmic design and parametric design.

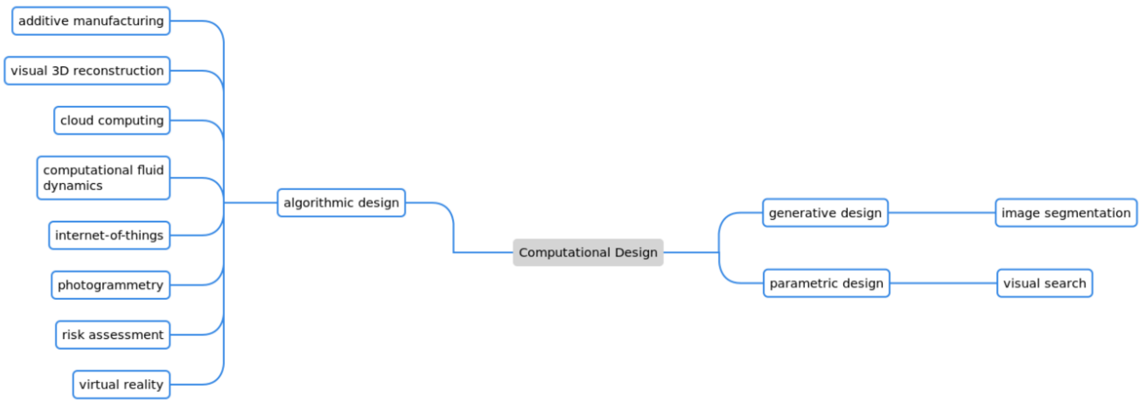

Figure 6. The re-occurring keywords in each computational design category

Some specific keywords appear in each category (Figure 6). Keywords majorly appear in the algorithmic design because it has much more scholarly work search data (68,441) compared to generative design (6,467) and parametric design (13,772). Nonetheless, they have the potential to be applied to each category.

Some keywords in algorithmic design (Figure 6) relate to the internet development (cloud computing and Internet-of-Things) and others to visualization (visual 3D reconstruction and photogrammetry). Cloud computing is an internet-based operation with an on-demand ability to share data with different devices [72]. Internet-of-Things (IoT) is the technology that connects electronic appliances to the Internet and other devices [73]. Meanwhile, visual 3D reconstruction is a procedure in computer vision that reconstructs scenes in 3D from pictures [74]. Photogrammetry is a metric imaging technique that permits digital reconstruction of a real object in 3D [75]. The internet technological advancement brings new possibilities for current functions, while visualization technology aids designers in generating digital reconstructions. Thus, they are equally relevant for helping designers.

On the other hand, other keywords in algorithmic design (Figure 6) also show implementations in multiple fields: additive manufacturing, virtual reality, computational fluid dynamics, and risk assessment. Additive manufacturing is a method that produces as-designed formations [76] by constructing consecutive layers of material [77] and is regularly acknowledged as 3D Printing [78]. Virtual reality (VR) is a three-dimensional technology where users can experience the virtual world with various senses [79], while it can automatically identify users' inputs and adjust the virtual world [80]. Computational Fluid Dynamics (CFD) is a systematic examination that interprets and investigates fluid flow obstacles with computer simulation [81]. Meanwhile, risk assessment is a method that involves three steps: risk identification, analysis, and assessment which presents a foundation for risk management [82]. They have equally significant functions in computational design.

Other keywords appear in generative design and parametric design. Image segmentation appears in the generative design search result (Figure 6), and it is the method of dividing a picture into more notable representations [83]. On the other hand, the visual search appears in the parametric design search result (Figure 6). It is a perceptual task to identify a search target object among other objects by following and interpreting a person's overt behavioral cues [84]. It is helpful for the deep learning image segmentation model to generate natural scenes. The functions equally serve a notable role in design and visualization.

Generally, the emerging trends in algorithmic design, generative design, and parametric design are artificial intelligence, computation, machine learning, visualization, and internet technology. They help designers generate their projects based on parameters and algorithms. Artificial intelligence and machine learning simplify the design process in computational design. Computation, internet technology, and visualization produce new possibilities and functionalities for designers. While automation may be a problem for designers, certain functions can benefit them. Designers should decide what should be automated and better as a manual task [85]. It can help them design faster and more efficiently if they understand applying certain technology advancements. In the end, the integration of technology and design processes can generate more satisfying designs if implemented wisely by designers.

4 CONCLUSION

Each computational design category has different numbers of keywords because it correlates with the number of search results. The parametric design had the most search result on The Lens, while algorithmic design had the least number of search results; hence, the parametric design had the most keywords appear in the analysis. Several themes emerge from the analysis, including artificial intelligence, computation, machine learning, visualization, and internet technology. Technology advancements should not be a hindrance to designers. Meanwhile, automation can be an obstruction to designers if not treated wisely. Artificial intelligence can be beneficial for architects to help generate solutions to complex and layered problems. Computers can generate vast possibilities to answer design issues with the help of algorithms and parameters. It is vital to decide what should be automated and better as a manual task. In conclusion, technology integration can produce more satisfying designs if executed intelligently. The trend analysis needs to be continued in other computational design categories to find continuity in the findings.

There were several limitations in this study. The bibliometric analysis might not be accurate to determine occurring trends in the architectural practice. Research explores possibilities, while the current architectural practice may not widely apply the findings yet. Meanwhile, the scholarly work data might have included studies in other fields (for instance, health or IT), as the search results were more than 1,000 in each category. It also might affect the keywords generated in the study, especially less mentioned keywords. There is a need for more studies regarding trends in computational design to foresee the direction of future research in architecture.

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