CLICKING IS ALL YOU NEED: IMPLEMENTING WAVE FUNCTION COLLAPSE IN EARLY-STAGE DESIGN FOR MANUFACTURING AND ASSEMBLY PROJECTS

OWEN ZHIYUAN LU[1], LEO LIN MENG[2], CRISTINA RAMOS JAIME[3] and M. HANK HAEUSLER[4]
[1234]Computational Design, School of Built Environment, University of New South Wales
[2]Data-Driven Design, HDR Inc.
[1]Zhiyuan.lu@student.unsw.edu.au, 0009-0006-1683-4714
[2]Leo.meng@hdrinc.com, 0000-0002-6279-9052
[3]c.ramos@unsw.edu.au, 0000-0002-6868-8855
[4]m.haeusler@unsw.edu.au, 0000-0002-8405-0819

Abstract. Wave Function Collapse (WFC) is a constraint-solving algorithm inspired by the quantum mechanics process. However, few attempts have been made in the Architectural, Engineering, and Construction (AEC) industry. WFC literature indicates that it is constrained by its low-fidelity, stochastic process, making it hard to apply in real-world designs, hence its potential lack of application in the AEC sector. Yet this research sees an opportunity in Design for Manufacturing and Assembly (DfMA). Unlike typical architectural projects, DfMA is often more constrained due to modularity. How the DfMA modularity benefits and constricts the spatial planning process, and if such a priori modular definition better informs the design process, is yet to be explored. Thus, how can the highly constrained spatial rules in DfMA architectural design be used in implementing WFC for higher-fidelity fast design concept prototyping? During the research, a prototype was experimented with and implemented while demonstrating several advantages jointly inherited from both the DfMA and WFC, namely (a) high-resolution rapid prototyping with little user intervention for early-stage DfMA and (b) further building material and topological analytics, were enabled for decision support. Hence, this paper addressed the rarely discussed early-stage design problems in the DfMA lifecycle and contributed to a real-world architectural project-based implementation of WFC integrated into an automated computer-aided architectural design workflow inspired by DfMA's modularity that aligns with Sustainable Development Goals (SDGs) of 11 Sustainable Cities and Communities and 12 Responsible Consumption and Production.

Keywords. Wave Function Collapse (WFC), Decision Support Tool, Computational Design, Design for Manufacturing and Assembly (DfMA), Modular Building and Construction.

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 1, 303-312. © 2024 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

1. Introduction

The wave function collapse (WFC) is a novel heuristic algorithm based on given spatial constraint rules. Compared to its rarity in AEC applications, it has been widely adopted in the video gaming field for generating mass assets procedurally with little human input. While it offers a simple approach for generating multiple outcomes according to neighbouring rules, the process is noted to be stochastic (Chasioti, 2020; Villaggi et al., 2023). Design for Manufacturing and Assembly (DfMA) is a field with increased interest in academia and the AEC industry for its promise of shortening project duration from the design to construction stages and maximising off-site prefabrication and functions here as a case study for WFC (Laovisutthichai & Lu, 2021). While this research applies DfMA as a framework of exploration, it does not aim to contribute directly to DfMA – thus the discussion on DfMA will be limited however we refer to the following listed references as literature review in the field (Abd Razak et al., 2022; Abrishami & Martín-Durán, 2021; Mesa et al., 2020; Tan et al., 2020; Yuan et al., 2018). In the architectural industry, the typical approach towards spatial planning in early design stages is usually illustrated via massing blocks due to the lack of detailed design information on day one of the projects. Such a technique normally trades off its fidelity in return for speed of prototyping, and it limits the applicability of computational analysis that requires higher model fidelity. We ask the following research question: How can we use WFC and DfMA to (1) rapidly generate higher fidelity spatial models with limited user input, (2) allow the generated model to adhere to given spatial planning constraints, and (3) use the generated model for further geometrical-intense computational analysis? Consequently, the research provides a workflow in early-stage architectural spatial planning that is quicker than massing modelling and generates higher-resolution models, which simultaneously benefits the decision-making process.

2. Literature Review

Wave Function Collapse (WFC) is derived from quantum mechanics. It describes the process where multiple possibilities at each superposition with unique different outcomes are constrained to one single state due to external interactions after an observation (Von Neumann, 1955). It has been widely adapted and applied in the video game industry as a constraint-solving algorithm, due to its simplicity and efficiency in procedurally generating mass assets with flexibility using little human input (Gumin, 2016). Its principle could be akin to an automatic sudoku solver, with multiple possibilities in each grid that are affected by results in adjacent cells and will influence subsequent moves. In this case, numerous building modules could be fitted onto the grid system, similar to placing integers until the sudoku is solved or the wave function is collapsed (Sevkli & Hamza, 2019). It has been rarely discussed in AEC challenges, since only a few attempts were made on considerably low-resolution meshes based on 2D WFC neighbouring rules. For instance, Lin et al. (2020) combined WFC and Convolutional Neural Networks (CNNs) to train computers in the design of urban spaces using the existing urban database and then produced 3D Block models. Similarly, Lioret et al. (2022) assigned 2D WFC rules for creating 3D meshes using Generative Adversarial Networks (GAN), another type of machine learning. On the other hand, Chasioti (2020) used pre-modelled tilesets of various rooms as input to investigate WFC constraint rules in a higher dimension while providing arguably detailed building model results. In the meantime, Villaggi et al. (2023) research based on massing blocks could offer site solutions with multiple buildings and analytical data during its iterative generation process. Nevertheless, as Chasioti (2020) and Villaggi et al. (2023) noted, WFC has limitations that its constraints must be purely spatial, and the generation process is simple but stochastic.

In contrast with WFC, other heuristic algorithms, such as Genetic Algorithms (GA) and Cellular Automata (CA), are often implemented in research on computer-aided AEC fields. Cellular Automata (CA) shares similarities to WFC, it can also generate complex patterns on its grid system following given neighbouring rules, which has been well explored in AEC (Herr & Ford, 2016; Watanabe, 2002). Even though both CA and WFC are both grid-based algorithms, but CA is deterministic while WFC is probabilistic. Meanwhile, GA is also a widely researched heuristic algorithm inspired by the natural process of evolution, in which through iterations of the generation process, the best-fit candidates' parameters (gene) are selected, crossed, and mutated for the generation of the subsequent iterations. As a heuristic algorithm, GA does not guarantee the optimal outcome, but produces near-optimal results within the desired computational power. GA heuristics can be applied to a wide range of problems and optimise towards single and multiple objectives in numerous AEC applications (Latifi et al., 2016; Nisztuk & Myszkowski, 2019; Wang & Wei, 2021). Compared with algorithms for sole generative purposes, GA relies on iterations of generation and evaluation, which is inefficient for the design task assessed in this research. Hence, WFC may exhibit greater flexibility and variation in procedural generation compared with CA, while it can be computed efficiently compared with GA, allowing higher resolution models as cell inputs, as well as multiple possible states in each cell, with the potential of generating models with greater resolution, complexity, and flexibility.

As Tan et al. (2020) argued, Design for Manufacturing and Assembly (DfMA) has become a field of enquiry in academia and the AEC sector. It can be divided into levels such as prefabricated components, volumetric assembly, and modular buildings, according to the Royal Institute of British Architects (RIBA). DfMA highlights a unique construction approach that emphasises off-site prefabrication to the maximum possible extent, while on-site construction is kept to a minimum (Abd Razak et al., 2022). The ability to upgrade, repair, or modify each module or component allows for flexibility throughout the lifecycle and extended usage (Mesa et al., 2020). DfMA is closely tied with BIM integration processes, which Abrishami & Martín-Durán (2021) proposed to model prefabricated building parts as BIM family components, and Yuan et al. (2018) a BIM-based parametric design for DfMA prefabricated components, which can save time in the project design stage. These advantages led to additional gains in terms of sustainability, such as minimisation of material waste and embodied carbon, which aligned with Sustainable Development Goals (SDG) 11 Sustainable Cities and Communities and 12 Responsible Consumption and Production (Laovisutthichai & Lu, 2021).

WFC is an efficient heuristic algorithm for various generation purposes, but there are limited instances of successful implementation in AEC research. The research in DfMA suggests that high fidelity modular DfMA BIM models can be created at family component level, but it still requires manual design and modelling input to assemble these components into an integrated building model, thus may be unsuitable for early design stages where time and design input are limited. Therefore, in what ways can we use WFC to generate high-fidelity building prototypes using DfMA as a guideline that can be beneficial for early-stage spatial planning decision-making?

3. Research Methodology

Action Design Research (ADR) methodology is applied to this research, where four essential steps, including problem formulation, action planning, action taking, and evaluation and reflection are undertaken. This methodology further enables launching of additional research cycles to revise and adjust the initial plan, then act, reflect, and evaluate again to benefit industry-collaborated research, allowing opportunities to check and gain additional feedback from industry experts, ensuring the mentioned research outcome is produced successfully while demonstrating its advantages for the early-stage decision-making process. (Sein et al., 2011).

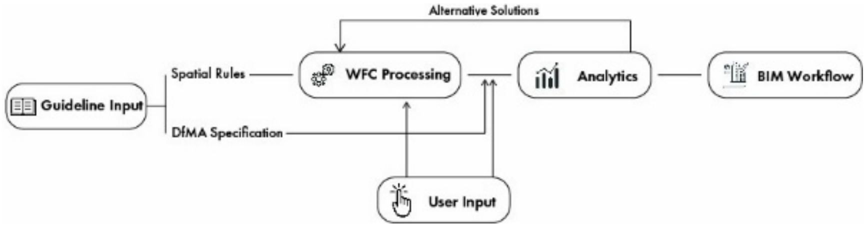

Figure 1 Project Workflow Diagram

During the first ADR stage of problem formulation, this research is partnered with AEC industry practice HDR Inc., to investigate a real-world issue regarding how WFC can be integrated as a new way of generating fast design prototyping. After identifying an issue in AEC practices with HDR, the actions for establishing a backend workflow were planned, and existing literature has been reviewed in terms of understanding the context background, state-of-the-art technology, software feasibility, etc. Then, the workflow outline was discussed and mapped out with the industry partner. Where the proposed tool is developed based on Rhino Grasshopper, including significant features such as DfMA guideline translation from spatial regulation pattern to adjunct rules, WFC processing and generation upon given rules, providing decision support and design analysis based on quick prototyping, along with an iterative process for continuous improvement. The plug-in, Monoceros, developed by SubDigitals is used for WFC processing in Rhino, since the tool is also planned to merge with HDR’s BIM workflow via Rhino Inside Revit. During the action-taking stage of ADR, all mentioned features are developed in Grasshopper, under industrial partner HDR's support, regarding both technical and real-world project content throughout weekly progress meetings. This research uses HDR’s real-world primary school projects as a case study, developed under New South Wales school infrastructure’s DfMA guidelines and principles (DfMA System Guideline, 2020).

4. Case Study

This research uses a primary school design project, a case study in New South Wales

(NSW), Australia to develop and test the WFC DfMA tool following the methodology explained above. The School Infrastructure department of NSW released guidelines to provide a consistent approach across NSW school projects and promote the DfMA technique for its advantages of sustainability, productivity and efficiencies.

Under the guidelines, Primary Schools have specific rules as listed in PS Example Standard Hub Layouts (2021). Projects involve a standard structural grid system of 7.5*9 (x*y) metres. Consequently, rooms with different functionalities can be volumetrically placed and assembled into the system. Within the document, precise spatial arrangement regulations have also been clearly stated. For instance, each Learning Common (LC) must be connected to multiple General Learning Spaces (GLS). LC can be indoor or outdoor, which needs to be placed on the sides of the generated scheme and linked with 2 GLSs as an outdoor LC, or 4 GLSs as an indoors LC. Hence, such restricted spatial constraints allow the potential of implementing WFC to generate rapid building prototyping. Thus, how can the translation from guideline room arrangement regulations to WFC adjacency rules be beneficial to the decision-making process for architectural spatial planning?

4.1. ITERATION 1 - INITIAL EXPLORATION

In the first iteration, the essential aim is to extract spatial arrangement regulations and other parameters for instance the designated number of students, which is decisive regarding school sizing and number of modules required. This would be beneficial towards mapping out decision support logic from the guideline, followed by creating module models for the generation of WFC according to the guideline and testing the algorithm permissibility in the selected software and plugin, Grasshopper Monoceros. These extracted neighbouring rules needs to be scripted and validated, while ensuring the robustness during further modifications in upcoming iterations. For the moment, three different module types have been included, with corresponding 2D WFC adjacent rules, inherited from the typical hub layout sample (fig.2). General Learning Spaces are further categorised into GLS_L and GLS_R. This indicates whether they are located on Learning Commons's left- or right-hand side associated with the typical hub

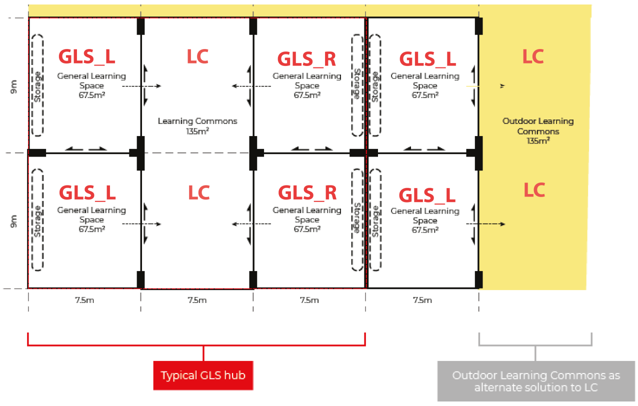

Figure 2 Module Definition to WFC Input

layout. Even though functionalities are identical, they are still spatially different from the modelling perspective. The first iteration's results showed that the tool can quickly generate low-resolution spatial planning options based on the grids controlled by sliders. It also highlighted some issues that merited further investigation: The assigned rules are not precise enough to guarantee that all the generated solutions are deterministic and meet the highly constrained DfMA guidelines. Additionally, the WFC-solving process is currently stochastic and uncontrollable by users, and the idea of decision support hasn't yet been addressed.

4.2. ITERATION 2 - SIGNIFICANT IMPROVEMENT

This stage further implements interaction, data analysis, and geometrical analysis components to provide the necessary functionality required in the conceptual design process. In this stage, module definitions were further divided to allow for more precise adjacency rules, because the established rules in iteration 1 could not guarantee that the produced solutions comply with the mentioned regulation. Besides that, Grasshopper Plugin Human UI and Mouse Rat have been used to create an interface with an interactive grid system to minimise stochastic process. As a result, users can click to generate design options at specific locations on the selected grids. Each click represents the addition of a new module, which the WFC solver will periodically activate to update and adapt to the latest user input. Furthermore, the interface offers information regarding school sizing categories, required GLS and LC numbers, and placed module numbers, subject to the student number input and current generated solutions relating to the guideline regulation. Overall, compared to the first iteration, the second iteration offers more user control over the generation process, rather than being completely random and reliant on spatial rules. Limitations arise when only a minimal level of decision support is addressed, and the current iteration can only produce solutions for a single level because 2D adjacency rules have been used.

Student Number 550
24 GLS & 6 LC Needed in Total
Still Need to Place 20 GLS & 4 LC
Medium / Core21

Figure 3 Iteration2 Results

4.3. FINAL OUTCOME

WFC adjacency rules are expanded to 3D to generate multi-level spatial planning solutions. The decision-support functionality of the tool has been improved with the capacity to provide beneficial feedback that helps assess each design option during rapid prototyping. For example, benefiting from the modularity of NSW's DfMA primary schools, the number of prefabricated components by each category and their volume, can be calculated given that existing DfMA system information is provided by NSW School Infrastructure. More importantly, building embodied carbon footprint breakdown can also be further estimated, since volume and materiality based on component category, are also assumed subject to the guideline. After that, the Grasshopper plugin conduit is used to provide live analytical graphs, updated every time a new module is placed, to assist users in exploring numerous design options in a short time. In addition, solar access analysis is also available via ladybug, to establish an understanding between the building and its surrounding environment. The tool has been integrated with the industrial partner's developed BIM model generation workflow. Once the design option is explored in the WFC-powered prototyping tool, the user can export the solution to Revit and complete a BIM model within seconds, as part of the automated workflow benefits of computer-aided design (fig. 5). Thus, the research demonstrates the potential of implementing WFC to generate detailed models and addressing highly restricted spatial planning constraints inherited from a DfMA process.

Student Number 550
Size Medium / Core21

	REQUIRED	LEFT TO PLACE
GLS	24	0
LC	6	0

Wall Material Timber
Structure Material Timber
Embodied Carbon Estimation: 382765.1 kgCO2eq
On
Off

Student Number 230
Size Small / Core7

	REQUIRED	LEFT TO PLACE
GLS	10	0
LC	3	0

Wall Material Timber
Structure Material Timber
Embodied Carbon Estimation: 148072.15 kgCO2eq
On
Off

Figure 4 Final Iteration Results

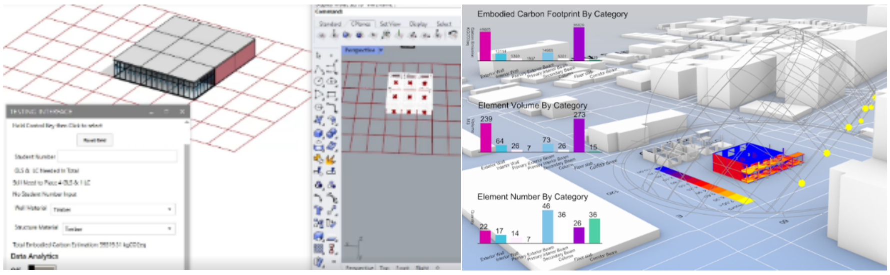

Figure 5 Merge with BIM quick generation workflow & Solar Analysis

5. Discussion and Future Steps

To highlight the aim of this study, A tool that is applicable to real-world AEC practices and their DFMA project workflows has been explored, inspired by both DFMA's spatial modularity, and the novel generative algorithm of Wave Function Collapse's characteristics of simple asset generation process based on constrain solving. This successful attempt indicated by utilising WFC in real-world DfMA projects, the generated model has higher geometrical resolution inherited from the DfMA guideline, contrasting the typical industry practice approach of low-resolution massing. Those high-fidelity models further enable a variety of computational analyses, including prefabricated component counts, building embodied carbon breakdown, and solar access insights, allowing to compare each design option in real time. These details would not usually be accessible in the early design stage due to many factors have not yet been decided.

Yet, the tool is still under development and has some limitations. Firstly, the WFC implementation through the Monoceros plugin is limited to a rectilinear grid system, which prevents more complex building typologies, as curved building blocks, or multiple buildings, from being placed at an angle. Secondly, the control of the WFC stochastic process is yet to be fully addressed. In the case study, we have used DfMA principles and spatial adjacency rules to provide controlled outcomes for the project. This applies to most DfMA projects with associated strictly defined spatial rules and modules, rather than specific to this case study. DfMA can be seen as a special case of building design, and the adaptability for non-DfMA building typology is subject to future testing. Based on the limitation discussed above, a series of further works are proposed: (1) implement WFC on an irregular grid basis for AEC applications and further test irregular modules and angled building placement (2) introduce a global and local weight system to introduce more finetuned user control over probability during tile generation, similar to the generation process proposed Villaggi et al. (2023), (3) include more analytical functions that are relevant to early stage spatial planning, such as traversal distance, wind/ventilation analysis, or regulatory compliance.

6. Conclusion

The study investigates the integration of the novel WFC algorithm into the initial phase of DfMA in architectural spatial planning. Through literature review, the research highlights previous WFC implementations that could be relevant to AEC applications, while also identifying limitations in tileset control. Further review of DfMA indicates that combining WFC with DfMA guidelines may enhance the early-stage architectural design. The study follows an ADR methodology to iteratively develop a tool and tested it in a real-world project as a case study and presents a real-world problem-focused implementation of the WFC technique in the AEC field. By incorporating DfMA principles into the generation process, the developed tool partly overcomes the previous constraint of lack of control. Moreover, the integration between WFC and DfMA enables the production of a high-fidelity model, generating analytics that were previously only possible at later design stages, rather than early conceptual designing via common massing blocks illustration. Compared to existing approaches using CA and GA, this tool significantly reduces generation waiting time with higher model resolution, and simplicity and intuitiveness of input. In addition, the analytical insights provide designers with better decision-making tools, and deliver the potential of data-driven design. In conclusion, the study shows how early-stage manual spatial planning can be streamlined to produce higher fidelity models in rapid speed and provides a novel means of client interaction that is more informative and engaging. It also emphasises the significance of DfMA's continued adaptation as a modern construction approach, aligning with SDG11 of sustainable city and community and SDG12 sustainable consumption and production patterns. Thus, such an automated process demonstrates the advancement in AEC computer-aided architectural design workflow integration and optimisation, indicating new opportunities for real-time design decision support for early-stage design projects.

Acknowledgements

The authors would like to thank Leo Meng for supporting the research project, and thanks to Luka-Luke Jovanovic, Rena Wang from HDR Inc. who have contributed architectural and modelling knowledge.

References

Abd Razak, M. I., Khoiry, M. A., Wan Badaruzzaman, W. H., & Hussain, A. H. (2022). DfMA for a Better Industrialised Building System. *Buildings*, 12(6), Article 6. https://doi.org/10.3390/buildings12060794

Abrishami, S., & Martín-Durán, R. (2021). BIM and DfMA: A Paradigm of New Opportunities. *Sustainability*, 13(17), Article 17. https://doi.org/10.3390/su13179591

Chasioti, E. (2020). Gameplay with encoded architectural tilesets: A computational framework for building massing design using the Wave Function Collapse algorithm. https://www.academia.edu/44870033/Gameplay_with_encoded_architectural_tilesets_A_computational_framework_for_building_massing_design_using_the_Wave_Function_Collapse_algorithm

DfMA System Guideline. (2020). School Infrastructure NSW.

Gumin, M. (2016). Wave Function Collapse Algorithm (1.0) [C#]. https://github.com/mxgmn/WaveFunctionCollapse (Original work published 2016)

Herr, C. M., & Ford, R. C. (2016). Cellular automata in architectural design: From generic systems to specific design tools. *Automation in Construction*, 72, 39–45. https://doi.org/10.1016/j.autcon.2016.07.005

Laovisutthichai, V., & Lu, W. (2021). Architectural Design for Manufacturing and Assembly for Sustainability. In S. S. Y. Lau, J. Li, S. Hao, & S. Lu (Eds.), *Design and*

Technological Applications in Sustainable Architecture (pp. 219–233). Springer International Publishing. https://doi.org/10.1007/978-3-030-80034-5_15

Latifi, M., Mahdavinezhad, M. J., & Diba, D. (2016). UNDERSTANDING GENETIC ALGORITHMS IN ARCHITECTURE. THE TURKISH ONLINE *JOURNAL OF DESIGN, ART AND COMMUNICATION*, 6(AGSE), 1385–1400. https://doi.org/10.7456/1060AGSE/023

Lin, B., Jabi, W., & Diao, R. (2020). Urban space simulation based on wave function collapse and convolutional neural network. *Proceedings of the 11th Annual Symposium on Simulation for Architecture and Urban Design*, 1–8.

Lioret, A., Ruche, N., Gibiat, E., & Chopin, C. (2022). GAN applied to Wave Function Collapse for procedural map generation. *ACM SIGGRAPH 2022 Posters*, 1–2. https://doi.org/10.1145/3532719.3543198

Mesa, J. A., Esparragoza, I., & Maury, H. (2020). Modular architecture principles – MAPs: A key factor in the development of sustainable open architecture products. International *Journal of Sustainable Engineering*, 13(2), 108–122. https://doi.org/10.1080/19397038.2019.1634157

Nisztuk, M., & Myszkowski, P. B. (2019). Hybrid Evolutionary Algorithm applied to Automated Floor Plan Generation. *International Journal of Architectural Computing*, 17(3), 260–283. https://doi.org/10.1177/1478077119832982

PS Example Standard Hub Layouts. (2021). School Infrastructure NSW.

Sein, M. K., Henfridsson, O., Purao, S., Rossi, M., & Lindgren, R. (2011). Action Design Research. *MIS Quarterly*, 35(1), 37–56. https://doi.org/10.2307/23043488

Sevkli, A. Z., & Hamza, K. A. (2019). General variable neighborhood search for solving Sudoku puzzles: Unfiltered and filtered models. *Soft Computing*, 23(15), 6585–6601. https://doi.org/10.1007/s00500-018-3307-6

Tan, T., Lu, W., Tan, G., Xue, F., Chen, K., Xu, J., Wang, J., & Shang, G. (2020). Construction-Oriented Design for Manufacture and Assembly (DfMA) Guidelines. *Journal of Construction Engineering and Management*, 146, 04020085. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001877

Villaggi, L., Stoddart, J., & Gaier, A. (2023). Harnessing Game-Inspired Content Creation for Intuitive Generative Design and Optimization. In C. Gengnagel, O. Baverel, G. Betti, M. Popescu, M. R. Thomsen, & J. Wurm (Eds.), *Towards Radical Regeneration* (pp. 149–160). Springer International Publishing. https://doi.org/10.1007/978-3-031-13249-0_13

Von Neumann, J. (1955). *Mathematical foundations of quantum mechanics.* Princeton, N.J. : Princeton University Press. http://archive.org/details/mathematicalfoun0613vonn

Wang, Y., & Wei, C. (2021). Design optimization of office building envelope based on quantum genetic algorithm for energy conservation. *Journal of Building Engineering*, 35, 102048. https://doi.org/10.1016/j.jobe.2020.102048

Watanabe, M. S. (2002). *Induction Design: A Method for Evolutionary Design* | SpringerLink (1st ed.). Birkhäuser Basel. https://link.springer.com/book/9783764366414

Yuan, Z., Sun, C., & Wang, Y. (2018). Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction*, 88, 13–22. https://doi.org/10.1016/j.autcon.2017.12.021