PARAMTR V2

Human-Generative Design tools for prefabricating large-scale residential developments.

JOSHUA JOE[1] and ANTONY PELOSI[2]
[1,2] *Victoria University of Wellington*
[1] *joejosh@myvuw.ac.nz* [2] *antony.pelosi@vuw.ac.nz*

Abstract. Designers are encountering more issues with complexity, scale and performance requirements increase in residential projects. Prefabrication and generative design tools have the potential to significantly reduce construction time, cost, and material waste at scale. Building upon existing research, this paper further investigates how human-generative design tools can improve building performance and feasibility of prefabrication at scale whilst encouraging design variance. In this context, human-generative design tools refer to a partially algorithmic design tool that facilitates an open-box, collaborative approach to design. Following initial research-based design, a new human-generative tool was created (PARAMTR) to address the aforementioned issues using a design-based research methodology. Based on the research performed during the literature review and from initial design results, PARAMTR shows the potential to halve construction time on residential projects in combination with increased manufacturing efficiency. Design outputs share no design commonality, yet use almost 10 times less unique components across four houses when compared to existing residential projects. In combination with the overall benefits discussed and associated with prefabrication, material waste, cost, design time and complexity are expected to be reduced. The paper will discuss further progress towards designing and building smarter homes at scale.

Keywords. Generative design; generative prefabrication; parametric; residential; prefabrication.

1. INTRODUCTION

As the world's population continues to rapidly accelerate, cities and countries are now facing some of the largest housing shortages in history - a problem that New Zealand is not excluded from. Despite the explosive demand for more residential projects, existing design and construction practices have failed to adapt as quickly, resulting in additional cost, time and construction limitations when working at an ever-increasing scale.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 1, 41-50.

Residential subdivisions of near-identical design are painstakingly constructed by hand, traditionally and on-site, at the risk of weather, quality defects and construction delays (Shahzad et al., 2015). Additionally, houses designed at present are not well-optimised for climate performance, with over 40% of New Zealand's housing stock damp or mouldy (NZGBC, 2020), including new builds.

Such problems can be largely addressed with the manufacturing and technological advancements of recent years. BIM, generative tools and fabrication have evolved to the point where a synergy of manufacturing efficiency, variety, quality and data-driven performance can be achieved at scale, and this is what the research paper focuses on. The objective of this research was to create, implement and investigate generative tools and prefabrication to enhance, accelerate and optimise the design and construction workflow of residential projects at scale.

2. Literature review - overall prefabrication concepts

Instead of relying on a singular proprietary prefabrication system that may become obsolete, superseded or inferior in time, the authors created a generative system that works with the fundamental concepts of prefabrication consistent across most systems, methods and types. Understanding this underlying "logic" was particularly important when creating PARAMTR. From research performed during the literature review, it was found that prefabrication methodologies typically benefit from having standardized components with less variation (J. Betz, personal communication, June 11, 2020). However, when working on large-scale projects, variation is inevitable and often required (Jaillon & Poon, 2010). Successfully maintaining distinct levels of modularity and variability allows the designer and/or end-user enough choices without compromising the economic and manufacturing benefits of production at scale and in volume (Gravina da Rocha et al., 2019).

3. Literature review - the construction industry & prefabrication

The benefits of prefabrication have been widely documented, particularly at scale and in comparison, to other methodologies. A New Zealand-based study found that up to 50% time reduction could be achieved in residential projects with standardised designs at scale (Shahzad et al., 2015) when compared to traditional construction. Two primary issues were identified as stopping the widespread adoption of prefabrication at scale. Designers have often struggled to balance variability and consistency of parts, not only on singular but also multiple projects and in a variety of site conditions (Jaillon & Poon, 2010). Any changes would require reconsideration of either existing prefabrication or design, often restricting and limiting design ability. Secondly, lack of awareness, increased risk, capital cost and stigmatism around prefabrication has led to banks, developers and companies being hesitant to procure projects not using a "tried and true" construction approach (Kulla, 2019). In addition, one of the authors currently works for a company that is producing houses at scale, at high volume. Such companies have enormous buying power and with the constant vertical integration of design, consultants and construction services, could easily incorporate manufacturing allowing for end-to-end control and cost benefits at scale.

4. Literature review - existing generative tools & software

As part of the literature review, the authors investigated several existing tools that fall within the research topics of this paper. The intention was to evaluate how a tool such as PARAMTR may contribute to existing work and research. A common limitation found amongst existing tools and research was that they often did not address or consider construction methodology. Tools such as Finch3D are "...a tool for Architects to leverage their designs in the early phases of a project" (FINCH, 2019) and are designed to accelerate the conceptual design process. Secondly, it was found that most tools do not actively take site conditions or climate performance into account. Whilst there are tools such as Ladybug Tools that provide accurate climate simulation, they mainly act as aids to an existing design, rather than actively creating, altering and developing design elements (Mackey & Roudsari, 2013). In addition, existing research highlighted the predominance of the "closed-box" computing approach, which has disadvantages when compared to an "open-box" approach (refer fig. 1). An open-box approach to generative tools allows for flexibility and adaptability, whilst avoiding the common weaknesses and limitations in both human and generative designers (Welch & Moleta, 2014). Prioritising the strengths and weaknesses of human and generative tools is particularly important when using these tools in an architecture and design context. Generative tools typically struggle to computationally "improve" design (Kalay, 1992), whereas humans struggle with vast amounts of data, numbers and complex problems with multiple variables (Peters & De Kestelier, 2013).

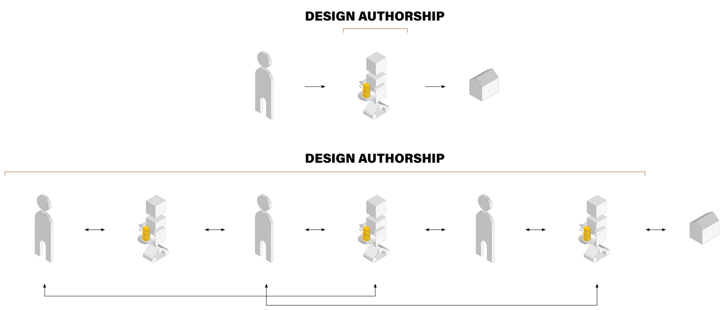

Figure 1. Whereas existing tools retain a 'closed-box' approach, PARAMTR was designed with an 'open-box' approach. Benefits of this approach include better collaboration between human and generative designer.

5. RESEARCH GOALS

PARAMTR aims to improve on existing prefabrication design strategies by enhancing designers with generative tools to reduce component complexity and variety. The tool also aims to balance standardization with flexibility, allowing for dynamic changes in both design and component variance on the fly. Finally, PARAMTR v2 should take into consideration climate performance and prefabrication logic, to ensure that any designs generated can be easily adapted to multiple systems and sites using the tool.

6. RESEARCH METHODS

6.1. RESEARCH FOR DESIGN

Research for design was performed at the start of the research with an in-depth literature review. The authors chose to perform a literature review to identify common weaknesses and strengths in existing research and software tools before producing PARAMTR. Relevant material was sourced from conference papers, peer-reviewed theses, books and digital tools used for investigation. Additionally, research for design was also performed throughout the design-based research phase. Although this method of research does not address personal opinion or theory, it ultimately resulted in more focused, efficient and relevant information gained before and during the design-based research phase. Identifying the existing context of the research was insightful and prevented the authors from 'doubling up' on existing work, whilst improving on and contributing to new areas of research.

6.2. DESIGN-BASED RESEARCH

As the research is evaluating the development and implementation of an enhanced generative system, design-based research was critical. Continual, rapid design-based research was critical for the authors to develop the generative tool in an agile, effective manner in response to both findings and additional research performed throughout the research period. The authors utilised a versioning number system with continuous evaluation before the development of the next version. Evaluations performed by the authors assessed computational, logical and practical constraints, with the next version addressing or eliminating any issues identified.

Based on the research performed in section 2.3, a combination of Rhino 7 and Grasshopper was chosen for the software platform of which this research uses. Grasshopper is a visual scripting generative program that interfaces with the popular BIM/CAD tool Rhinoceros 7. In addition to easily supporting workflows to Revit (a BIM program common in the architecture industry) (McNeel & Associates, 2019), the authors were familiar with both programs, which allowed for more time spent on the research rather than learning. Design-based research as a methodology was highly effective for this research due to the constant loop of investigation, design, evaluation and refinement. The authors could rapidly develop PARAMTR using software tools that enable agile, flexible and rapid research. Without design-based research, PARAMTR would not have been as rapidly developed or have fewer substantial findings.

7. PARAMTR v2 - how does an enhanced generative tool accelerate prefabrication at scale?

Whilst previous research documenting PARAMTR v1 focuses on the implementation of shared authorship and generative design strategies in residential design, this paper documenting PARAMTR v2 focuses on the feasible implementation of generative prefabrication tools particular focus on the produced outputs and prefabrication benefits (Joe & Pelosi, 2020). Although the tool itself is complete, the research is still in progress and thus any evaluation or conclusions reached are subject to change.

8. PARAMTR v2 - strategy, logic & methodology

A strategy was formed to implement efficiency and dynamic prefabrication using generative tools. Based on the research performed in sections 1.1-1.3, the underlying concept of prefabrication to be used in PARAMTR was clear - reduce the number of unique components, whilst balancing design variability and flexibility. A balance between human and generative tool was achieved by delegating all design aspects to the human, with all complex number and data-based problems handled by PARAMTR. As per the research in section 1.3, this ensured that each was performing tasks in their best strengths and with reduced weaknesses. This strategy begins from the initial conceptual design phase, where rooms and overall dimensions are standardised to identical dimensional tolerances (such as to the nearest 1000mm, 600mm etc). These tolerances mean the conceptual designs produced are practically constructible and adjustable to suit, with timber lengths to the nearest metre and plasterboard sheets typically in 600mm widths. Additionally, from the authors' industry experience overall dimensions are rounded regardless, with overall dimensions having little effect or limitation on the overall design. The initial floorplan is generated by PARAMTR, with additional design tweaks and circulation performed by the designer. This was found to be far more efficient compared to letting the generative system handle all design, which added 1-2 hours as opposed to the 4-5 minutes for a single author to make similar adjustments.

PARAMTR takes a "process of elimination" approach to prefabrication, with wall elements then gradually separated into smaller subsets depending on their function and requirements. Regardless of construction system, exterior and interior walls will differ in terms of both structural and environmental requirements. For this reason, walls are divided based on if they are exterior or interior. Exterior walls are then created with generatively informed windows (see section 3.5) that balance climate performance across all designs in all instances of each wall. Interior walls are then separated into those that do or do not require doorways (which will change construction requirements when compared to a uniform wall). The generative system then dynamically standardises components until there are a few unique parts as possible across all designs and all wall instances, exterior or interior (refer fig. 2). The result of this approach to generative prefabrication is a near-real-time system that can dynamically adapt to design changes, whilst maintaining manufacturing efficiency and climate performance at scale. Section 3.5 will further discuss the results.

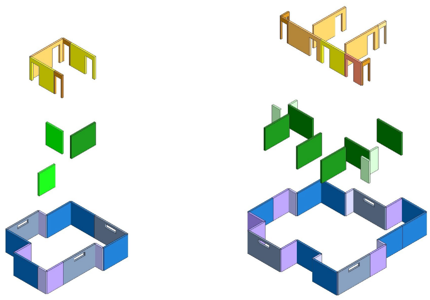

Figure 2. Wall components were optimised to as little variance within three categories - exterior, interior, and interior with door openings. .

9. PARAMTR v2 - results

As part of the ongoing research, initial design concepts were produced earlier this year based on an earlier version of PARAMTR (v1). 4 designs were produced generatively using PARAMTR v1 that shared no design commonalities in terms of layout, floorplan or type with unique program requirements, unique site conditions and priorities. These were then run through PARAMTR v2's new prefabrication logic to optimise the designs for standardised parts. Despite containing 127 total wall elements, only 16 elements were unique (refer fig. 3). By comparison, a single residential project with 42 total wall elements contained 33 unique elements. PARAMTR v2 represents a massive improvement in potential manufacturing and design time efficiency, with a single author able to produce all 4 designs in 90 minutes. When considering prefabrication, climate considerations and the sheer number of contributing factors dedicated to making design decisions with this logic, it would take a human designer far more time to reach the same level of complexity and efficiency at scale.

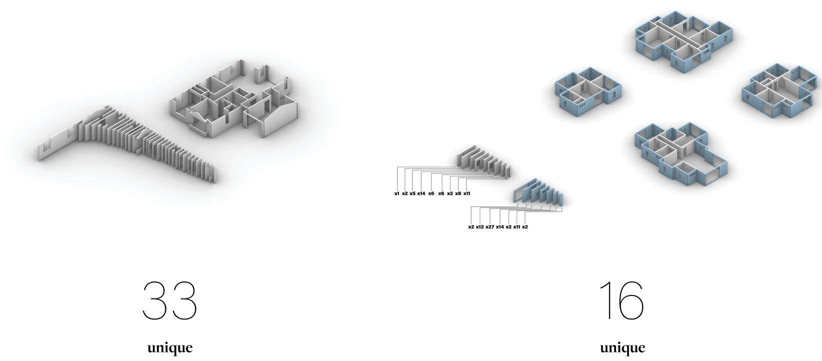

Figure 3. Four designs produced using PARAMTR v2 share 16 unique elements, whereas a single standard residential design has 33. Reduced variance in parts means increased manufacturing efficiency at scale.

PARAMTR v2 includes improvements designed to further reduce time spent and improve the overall practicality and quality of designs produced. Version 2 of PARAMTR includes a user interface (refer fig. 4) for faster workflow (which hampered time efficiency in v1), the ability to optimise up to 8 unique designs for prefabrication and also automatically size windows based on sunlighting performance per design, per wall instance, per location across all designs. It is also worth pointing out that the number of designs that could be optimised at once is arbitrary. Due to a limitation in Grasshopper, the authors have to manually add additional code repeaters for each additional design to be optimised - in theory, PARAMTR could evaluate and optimise 8 or more designs with a similar or greater level of efficiency.

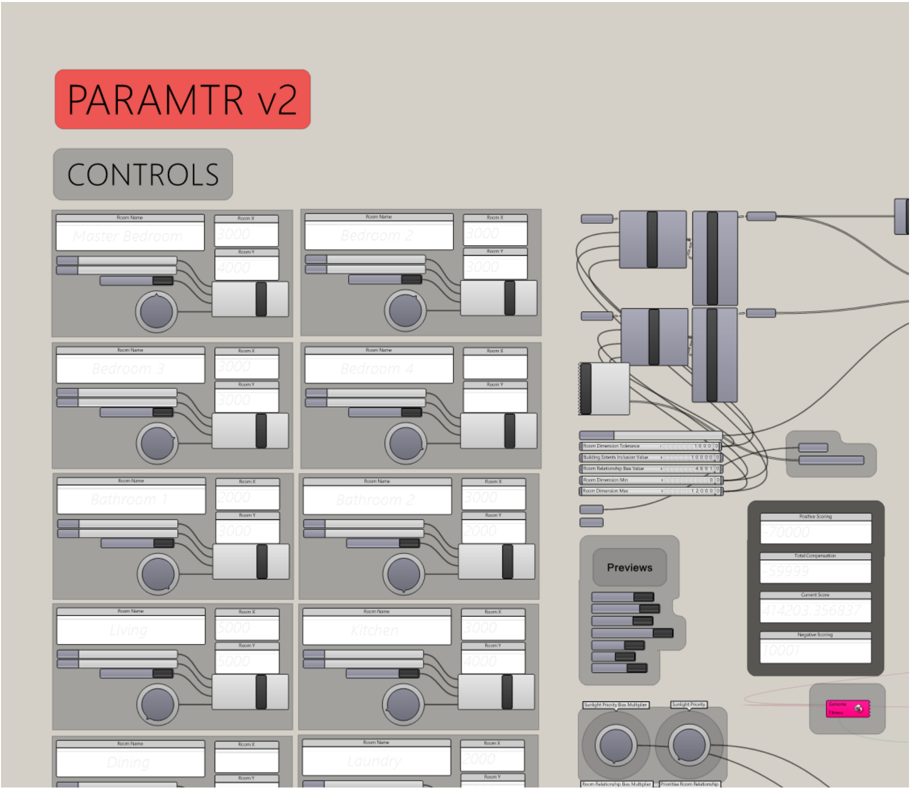

Figure 4. Amongst PARAMTR v2's improvements, a UI was developed which drastically reduced error rates and increased time efficiency when compared to v1.

Research to date in sections 1.1-1.3 indicates a construction time reduction of up to 50% (Shahzad et al., 2015), with significant economic gains and quality increases due to the benefits of manufacturing using economies of scale (Orlowski, 2020). Future research will address and evaluate tangible observations at a greater level of detail.

10. Critical reflection

Based on current research, the potential for a system such as PARAMTR to radically improve residential projects at scale is clear. Alongside massively reducing the overall design complexity and time associated with prefabricated residential projects, the benefits of prefabrication bring reduced material waste, construction time and cost. These benefits are particularly important at scale, where the rate of improvement is exponentially increased across multiple, large-scale projects. In addition, PARAMTR encourages design variance, with better performing, unique designs and with designers focusing more on the design rather than the numbers, data and calculations. This falls in line with the authors' goal of producing more houses at scale, better, faster and more cost-effectively.

However, the downside of PARAMTR's agnostic approach to prefabrication means that no specified prefabrication system or connections have been considered. In response, the authors will address this in future with the evaluation of existing prefabrication systems to demonstrate the feasibility of integrating PARAMTR. Additionally, the approach of production at scale requires extensive manufacturing facilities, of which there are few in New Zealand. These downsides should be considered when implementing a system such as PARAMTR, which may require tailoring to meet specific system and regional requirements.

In terms of limitations, this approach has only been applied to wall framing, with the current system designed for "green-field developments" - single-storey developments on relatively flat terrain. Whilst this is a limitation, the authors recognise that subdivisions are commonly built on mostly flat terrain in New Zealand, with most residential projects utilising a slab on grade for their flooring system. A similar approach could easily be taken to optimise the roof and flooring systems of houses at scale, based on existing research, systems and findings to date.

11. Conclusion

Research on PARAMTR proves that there are superior ways of designing and building residential projects at scale. Lack of innovation has cost the industry in time, cost and complexity. With generative tools and prefabrication advancing at a rapid pace, it is now possible to use these tools at scale to improve design and construction processes when working at scale. PARAMTR proves that combining a human-generative approach with prefabrication has the potential to reduce construction time by up to 50%, enable designers to produce 4 optimised, unique designs in under 2 hours and in turn increase productivity and quality for the masses. The authors imagine PARAMTR integrating into large-scale BIM developments, accelerating design processes whilst reducing construction cost and time. A tool like PARAMTR facilitates the ability to create greater design variety at scale, whilst substantially improving cost and time efficiency.

The research will continue to assess and evaluate the design outputs produced by PARAMTR, with tangible evaluations on aspects such as cost, time and quality benefits performed. The authors have chosen to not consider specific systems of prefabrication in the interests of keeping PARAMTR v2 agnostic to any prefabrication methodology. Future research could investigate creating a prefabrication system suitable for generative prefabrication, or investigate ways of designing with an existing, generated range of wall components.

The future in human-generative tools brings many benefits to an industry constantly struggling with an bespoke approach to construction and design. Research and implementation of forward-thinking technologies will enable our ability to build faster, at greater scales and more cost-effectively to rectify the global housing shortage.

Acknowledgements

This research was made possible by the BRANZ and Building Research Levy.

References

McNeel \, R.: 2019, "Rhino 7 Features" . Available from <https://discourse.mcneel.com/t/rhino-7-features/80163>.

Harness, C.H.: 2020, "TestFit Home" . Available from Library Catalog: blog.testfit.io<https://blog.testfit.io>.

Jaillon, L. and Poon, C.S.: 2010, Design issues of using prefabrication in Hong Kong building construction, *Construction Management and Economics*, **28**(10), 1025-1042.

Kalay, Y.E.: 1992, *Evaluating and predicting design performance*, Wiley, New York, N.Y.

Mackey, C. and Roudsari, M.: 2013, "Ladybug Tools" . Available from <https://www.ladybug.tools/ladybug.html>.

NZGBC, N.: 2020, "Budget boost for warmer homes will bring healthy, safe places for New Zealanders but leaves thousands in the cold." . Available from <https://www.nzgbc.org.nz/KNOWLEDGEHUB/Story?Action=View&Story_id=563>.

Orlowski, K.: 2020, *Automated manufacturing for timber-based panelised wall systems*, Ph.D. Thesis, University of Melbourne.

Peters, B. and De Kestelier, X.: 2013, *Computation works: the building of algorithmic thought*, John Wiley \& Sons, Chichester.

Gravina da Rocha, C., El Ghoz, H.B. and Jr Guadanhim, S.: 2019, A model for implementing product modularity in buildings design, *Engineering, Construction and Architectural Management*, **27**(3), 680-699.

Shahzad, W., Mbachu, J. and Domingo, N.: 2015, Marginal Productivity Gained Through Prefabrication: Case Studies of Building Projects in Auckland, *Buildings; Basel*, **5**(1), 196-208.

Wallgren, J.W.: 2019, "FINCH" . Available from Library Catalog: finch3d.com<https://finch3d.com/>.

Welch, C. and Moleta, T.J.: 2014, Selective Interference: Emergent Complexity Informed by Programmatic, Social and Performative Criteria, *ACADIA 2014*, **34**, 719-726.