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Integrating Design and Fabrication For Sustainable Housing: Insights From The Kopps Prototype

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Abstract: In the face of escalating housing challenges in Canada, including the urgent need for affordable, sustainable, and resilient living spaces, innovative solutions are critically needed. This paper aims to address these challenges by introducing the "Kit-of-Parts Platform System" (KOPPS), a pioneering approach that integrates design and fabrication processes. KOPPS represents a significant departure from traditional construction methods, promising to revolutionize the housing industry by enhancing efficiency, reducing costs, and minimizing environmental impacts. Through a comprehensive platform that combines upstream design activities through a web-based configurator with downstream construction production using digital fabrication technologies, KOPPS facilitates stakeholder collaboration, streamlines project management, and fosters the production of housing that is not only cost-effective but also environmentally sustainable and resilient. This paper also showcases the innovative aspects and scalability of KOPPS across various housing types, highlighting its contributions to sustainability and social equity. Ultimately, this exploration calls for broader collaboration among policymakers, industry stakeholders, and researchers to adopt and further develop technologies like KOPPS, paving the way for a future where sustainable and affordable housing is accessible to all.

Keywords: Sustainable Housing; Design Platform System; Design-Fabrication Integration; Digital Fabrication.

1 INTRODUCTION

Acknowledging complexities of Canada's housing landscape reveals the diverse and significant challenges it encounters. At the forefront of these challenges lies the affordability crisis, with a considerable number of Canadians struggling to find housing that remains within their financial means. Recent studies and reports highlight that around one in five Canadian households are burdened with housing costs exceeding 30% of their pre-tax income, a situation that is expected to deteriorate with the intensifying housing shortage (Randle et al. 2021, Cournède and Plouin 2022, Statistics Canada 2022, Choi and Ramaj 2024). This affordability issue is exacerbated by rapid urbanization and demographic growth, which escalate the demand on an already constrained housing supply. Moreover, environmental sustainability has emerged as a paramount concern, reflecting the need to address the significant ecological footprints of construction practices and building lifecycles. The housing sector in Canada is a major consumer of resources such as energy, land, water, and raw materials, contributing substantially to the country's greenhouse gas (GHG) emissions (Canada Mortgage and Housing Corporation 2018). Consequently, there is a pressing demand for construction materials and methods that minimize carbon emissions and improve energy efficiency.

Ultimately, the surge in extreme weather events also necessitates a transition toward building homes that are safe and resilient to climate-related challenges. The aging infrastructure compounds these issues, with 76% of Canada's rental units being over 36 years old, indicating a significant portion of the housing stock requires urgent renewal and retrofitting to meet current standards of safety and efficiency (Tower Renewal Partnership 2017). Additionally, the escalating frequency and severity of natural disasters and extreme weather conditions across Canada highlight the critical need for efficient, resilient housing solutions and rapid reconstruction efforts for homes impacted by such events (Benson 2022). Therefore, the pressing need for innovative and effective strategies to ensure resilient and sustainable housing in Canada is highly demanded.

Prefabrication, also known as industrialized, offsite, or modular construction, presents a promising approach to mitigating the challenges of affordability and sustainability in housing. This method involves assembling building components in a factory setting before transporting them to the construction site, thereby enhancing construction efficiency and quality (Zhang et al. 2020, Cheng et al. 2023). This process is also significant in reducing on-site costs and environmental waste. However, despite its potential, the widespread adoption of prefabricated housing faces constraints due to the limited availability of low-cost ready-built prefabricated homes and the elevated expenses associated with custom-made designs. Each construction site presents unique challenges, necessitating customized solutions for areas particularly vulnerable to natural disasters, such as floods or wildfires in Canada. A critical consideration in prefabrication is balancing the need for customization with the economies of scale achievable through factory production (Farr et al. 2014). To address Canada's escalating housing needs effectively, there is an imperative to advance traditional prefabrication technologies. The goal is to enable the production of mass-customized homes that are not only affordable and of high quality but also scalable, thereby making resilient housing more accessible across the country.

To address these challenges, this paper introduces the "Kit-of-Parts Platform System" (KOPPS), an innovative approach that supports prefabrication by integrating design and fabrication processes. This integration offers a highly effective solution for achieving mass customization in the construction of affordable and resilient homes. KOPPS utilizes a web-based configurator to treat each housing project as a modular product platform. It configures construction components from a predefined kit-of-parts according to specific construction and installation rules and limitations. Defined in the industry as a collection of pre-engineered and designed discrete building components, these kits can be assembled in various configurations to create a complete building, promoting both versatility and customization (Howe et al. 1999, Cao et al. 2021). The essence of the kit-of-parts methodology lies in its ability to combine versatility with customization, scaling up construction processes while ensuring sustainability. Additionally, KOPPS employs robotic manufacturing to facilitate and expedite the production of these kit-of-parts-generated building components, enhancing precision, efficiency, and overall construction quality.

The second objective of this paper is to explore KOPPS's potential as a scalable solution to Canada's housing challenges. By standardizing parts while enabling diverse architectural layouts, KOPPS effectively addresses the critical demands for affordable and customized housing. The integration of digital tools and technologies in KOPPS enhances precision and efficiency, significantly reducing the waste, time, and expenses typically associated with conventional construction methods. Specifically, the integration of robotic manufacturing techniques in KOPPS further optimizes the cost, time, and quality efficiencies of the final building components. The application of industrial robots in production not only adds manufacturing flexibility but also enables the creation of unique and customized components, catering to specific construction needs (Bhatt et al. 2020).

Moreover, KOPPS's automation of the design and fabrication processes, including the seamless flow of data from design to fabrication, democratizes the development of resilient and sustainable housing. This approach makes such vital features more widely accessible, enhancing the potential to meet the diverse housing needs of the population. Through the examination of KOPPS's framework and potential, this paper highlights how integrating digital innovations in design and construction can provide tangible solutions to the affordability, sustainability, and resilience crises plaguing the housing sector. By exploring these aspects, the paper seeks to contribute to the ongoing dialogue on housing innovation, offering insights into the benefits of modular construction and digital fabrication in meeting contemporary housing needs. The following sections will delve into a brief introduction of KOPPS and its main components and features, followed by a discussion on the expected advantages of this approach in Section Three, and concluding with insights and future directions. It is important to note that the development of KOPPS is beyond the scope of this paper; instead, this work serves as an introduction and exploration of this innovative platform.

2 KIT-OF-PARTS PLATFORM SYSTEM (KOPPS)

In addressing the pressing concerns of affordability, sustainability, and resilience in Canada's housing sector, the "Kit-of-Parts Platform System" (KOPPS) emerges as a pioneering solution, incorporating advanced digital tools to revolutionize the design and fabrication of housing. This section delves into the operational dynamics and components of KOPPS, particularly focusing on the KOPPS Configurator and the KOPPS Digital Fabricator, which are pivotal cores of this innovative approach.

2.1 KOPPS Configurator

The KOPPS Configurator represents a web-based, innovative product platform designed to empower stakeholders in the housing construction sector by facilitating the generation of customizable, code-compliant designs optimized for digital fabrication. The Configurator is structured around three core components:

2.1.1 Generative Design Module: Utilizes diffusion algorithms to automate the generation of housing layouts based on user-defined functional requirements and constraints, including budget and lifestyle preferences. This module significantly reduces preliminary design time while maintaining customization, outputting multiple design alternatives in formats compatible with Building Information Modeling (BIM) software and IFC standards for further refinement and compliance checks.

2.1.2 Smart Recommendation for Procurement: Integrates a hybrid recommender system combining knowledge-based filtering and text mining to streamline the selection of construction materials and components. Leveraging BIM data, the system optimizes product selection based on compatibility with project specifications and user preferences, enhancing transparency and efficiency in the procurement process.

2.1.3 Programming and Interoperability: Built on a three-tier architecture (presentation, application, data), the Configurator ensures seamless data exchange and scalability. It supports various data formats and interfaces, enabling integration with other software systems (e.g. robotic programming platforms) and facilitating collaborative design and decision-making processes.

2.2 KOPPS Digital Fabricator

The Digital Fabricator component of KOPPS integrates the design data from the Configurator with robotic fabrication processes, embodying the transition from digital to physical in the construction of building elements. This process encompasses:

2.2.1 Extraction and Translation of Design Data: Custom plugins for the BIM environment and a local database system facilitate the extraction of detailed BIM data, which is then translated into executable instructions for robotic fabrication, emphasizing precision and efficiency in producing building components.

2.2.2 Robotic Fabrication Simulation and Programming: Utilizing a stand-alone robotic programming platform, the framework simulates the fabrication process, allowing for pre-execution optimization and adjustment. This phase involves the creation of a virtual environment that mirrors the physical setup, including the robot's movements and interactions with construction elements, ensuring a direct correlation between the digital design and its physical instantiation.

2.3 Integration and Workflow

The methodology articulates a seamless workflow that begins with the digital conception of a housing project in the Configurator, spanning design generation, material selection, and procurement optimization. The process transitions to the Digital Fabricator, where design data becomes the blueprint for robotic construction, emphasizing sustainability, efficiency, and precision. This integrated approach not only streamlines the housing construction process but also fosters innovation and sustainability in building practices.

3 DISCUSSION

The Kit-of-Parts Platform System (KOPPS) represents a groundbreaking approach in tackling the complex challenges of today's housing crisis. This section delves into how KOPPS leverages its innovative framework to introduce scalable, sustainable, socially impactful, and accessible housing solutions, marking a significant leap beyond traditional construction methodologies.

3.1 Scalability Across Housing Types

KOPPS's digital and modular foundation transcends the limitations of traditional prefabrication, offering scalable solutions adaptable to a wide array of housing demands. Moving away from the one-size-fits-all approach of conventional prefabrication, KOPPS embraces adaptability and customization to meet specific client needs. Its capability for integrated design, automated fabrication, and seamless flow of data from design to fabrication enables the swift delivery of cost-efficient, flexible housing designs. From individual homes to extensive urban developments, KOPPS's versatility addresses the critical demand for diverse and affordable housing options.

3.2 Sustainability and Environmental Impact

Sustainability is at the core of KOPPS's philosophy. By incorporating Life Cycle Assessment (LCA) tools directly into the design process, KOPPS equips decision-makers with the insights needed to minimize environmental footprints effectively. This proactive approach in material selection and design strategies heralds a new era of environmental stewardship within the construction sector. Moreover, the KOPPS Digital Fabricator epitomizes efficiency, minimizing waste and optimizing resource use through precision in robotic fabrication, underscoring KOPPS's commitment to eco-friendly construction practices.

3.3 Social Implications and Accessibility

KOPPS stands out for its potential to address the social dimensions of the housing crisis. By integrating construction and design knowledge on a single platform, KOPPS ensures that the benefits of resilient housing solutions are accessible to a wider demographic. In addition, the platform's potential to capture and disseminate construction knowledge amplifies its social impact, enabling a continuous improvement cycle that benefits future projects and communities.

The integration of advanced digital tools with practical construction knowledge through KOPPS paves the way for a future where housing is not just a commodity, but a tailored solution that addresses the unique needs of communities worldwide. By adopting KOPPS, various stakeholders like customers, architects, and developers can leverage its potential to deliver housing solutions that are not only economically viable and environmentally responsible but also culturally and socially enriching. Therefore, it is imperative for policymakers, and community leaders to actively support and promote the adoption of KOPPS, recognizing its potential to transform the housing sector and contribute significantly to solving the housing crisis.

4 Conclusion

The "Kit-of-Parts Platform System" (KOPPS) introduces a revolutionary approach to address Canada's housing crisis, focusing on affordability, sustainability, and resilience. By utilizing cutting-edge digital technologies and adopting a modular design and fabrication strategy, KOPPS overcomes traditional construction challenges. This method offers scalable and customizable housing solutions that meet a wide range of needs. The system's flexibility, automation, and scalability lead to significant improvements in efficiency and cost reduction, making personalized and durable homes accessible to everyone. Additionally, KOPPS integrates sustainability assessment tools and promotes a seamless digital-to-physical construction process, significantly minimizing environmental impact while optimizing material use and decreasing waste. As KOPPS sets new standards for housing development, it encourages architects, developers, policymakers, and community leaders to support this innovative model. Adopting KOPPS represents a collective move towards a future of housing that is more sustainable, equitable, and tailored to individual needs, where every construction endeavor positively affects both the environment and society.

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