

Digital Participation in Sustainable Urban Densification

Exploratory Design Methods for Timber Building Stock Extensions

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Abstract. The accelerating pace of urbanisation and population growth, coupled with escalating climate challenges, necessitates sustainable and socially inclusive strategies for urban densification. Conventional construction practices, dominated by concrete and steel, contribute substantially to global carbon emissions, while existing multi-storey timber systems restrict architectural freedom through rigid, grid-based or modular configurations. This study explores how computational methods can extend the applicability of an existing multi-storey timber system—currently used only for new developments—to the design of building stock extensions. Unlike conventional approaches, the proposed computational design methods establish a feedback loop between the building system and design, enabling multi-variate extensions that support adaptable and versatile architectural outcomes while ensuring feasibility through the integration of regulatory constraints in the early design phase. A browser-based configurator was developed to facilitate early-stage, socio-technical co-design. By leveraging complex computational definitions and real-time simulations on the web via Rhino Compute, stakeholders from diverse backgrounds can explore various densification scenarios and make informed, evidence-based decisions regardless of their design or computational expertise. Evaluation across three case studies, demonstrates the design’s flexibility and reveals the hitherto untapped potential of computational design methods in promoting sustainable, regenerative, and socially inclusive urban densification with computational timber systems.

Keywords. Digital Participation, Sustainable Urban Densification, Computational Design Methods, Computational Multi-storey Timber Systems, Design Exploration, Evidence-based Design

1. Introduction

Cities around the world are increasingly confronted with complex and interconnected challenges, driven primarily by rapid population growth, accelerating urbanization, and climate change. By 2050, cities are projected to absorb two-thirds of the world's population growth, with towns accommodating most of the remainder (UN, 2025). Meeting the resulting demand for additional building volume and supporting urban infrastructure raises critical environmental concerns. In 2023, the buildings and construction sector accounted for approximately 34% of global energy-related CO₂ emissions, including 26% from operational energy use and 8% from embodied carbon associated with construction materials, while simultaneously generating roughly one-third of global waste (UNEP, 2025). At the same time, housing shortages in high-demand areas drive broader societal challenges, including inequality, weak productivity, health issues, and climate change (Myers et al., 2021).

To address these challenges, urban policies must urgently promote climate-friendly densification strategies alongside socio-ecological architectural solutions. Key priorities include using low-carbon and renewable materials, improving energy and material efficiency, minimising construction and demolition waste, adapting and retrofitting existing buildings, constructing flexible, adaptable, long-lasting new structures that can accommodate future changes in use, and effectively leveraging digital technologies. Interdisciplinary stakeholder engagement is also essential in raising public awareness and support, and in providing the expertise and contextual knowledge needed to develop inclusive, sustainable and resilient urban solutions.

1.1. TIMBER BUILDING STOCK EXTENSIONS & THEIR CHALLENGES

Building Stock Extensions (BSEs) offer a practical solution to urban spatial limitations and provide valuable environmental benefits, such as minimising waste, preserving green spaces, and mitigating transportation emissions caused by urban sprawl. The advantages of BSEs are amplified when they employ light-weight timber building systems. Wood offers a viable and responsible approach to multi-storey construction that encompasses all three pillars of sustainability: environmental, economic and social.

For instance, wood, as a renewable material with carbon-sink potential, helps mitigate resource scarcity and curb global warming. The projected surge in urban construction over the coming decades, combined with sustainable forestry practices, material substitution, and the creation of long-lived structures, offers a unique opportunity to transform the built environment into a large-scale carbon sink (Churkina et al., 2020). Economically, locally sourced timber can strengthen regional forest value chains, enhance self-sufficiency, and improve resilience to climate-related disturbances and global market fluctuations (García-Jácome et al., 2025). With a high strength-to-weight ratio, mass timber enables lightweight structures (Harte, 2017). This is highly relevant for vertical extensions, reducing the need for costly structural reinforcements. Off-site fabrication further accelerates construction time, improves scheduling precision, and allows continued use of existing buildings. Socially, timber supports regional craftsmanship and revives culture-specific construction methods. It also enhances occupant well-being thanks to its biophilic qualities.

However, several challenges accompany building stock extensions with timber.

Most multi-storey timber building systems (MsTBS) rely on repetitive structural grids or modular layouts and often incorporate steel or concrete hybridisation. They also favour rectilinear geometries and limited spans (Svatoš-Ražnjević et al., 2022). As a result, their applicability in complex urban environments is constrained. The structural components of many existing urban buildings are predominantly composed of concrete or steel and accommodate long spans and irregular geometries. Consequently, urban densification requires structurally and geometrically flexible design solutions capable of adapting to irregular site constraints, mixed-use programmes, non-rectilinear forms, non-grid-based support conditions, while enabling large spans and direct, vertical extensions of existing supports, thus avoiding the need for costly load-transfer layers.

1.2. COMPUTATIONAL TIMBER FOR BUILDING STOCK EXTENSIONS

A point-supported flat slab system for multi-storey timber construction was developed at IntCDC, University of Stuttgart (Krtschil et al., 2022) using a co-design methodology that integrates (1) computational design and engineering methods, (2) robotic fabrication and construction processes, and (3) novel material and building systems (Orozco et al., 2023).

The system's key characteristics are particularly relevant for building stock extensions (BSEs) and include: (a) material efficiency, (b) design freedom, (c) structural intelligence, and (d) fabrication scalability. Specifically, the mono-material hollow slab achieves material savings of up to 40% while enabling multidirectional spans and spatial flexibility comparable to reinforced concrete slabs. Its independence from a rigid structural grid allows supports to be positioned freely, facilitating alignment with existing structures and adaptation to irregular building geometries. Structural intelligence is further enhanced through algorithmic design tools that optimise the placement and orientation of internal webs along principal stress trajectories, improving load-bearing efficiency. Finally, the system's scalability is supported by its compatibility with flexible, digitally driven fabrication methods, particularly robotic manufacturing, enabling efficient production of geometrically unique elements, while reducing labour and construction time.

The IntCDC MsTBS is currently being tested through the construction of 1466m² of point-supported timber slabs in a large-scale demonstrator building - the IntCDC Building Demonstrator (Figure 1) (Treml, Riedel et al., 2025).



Figure 1. Left: section of the IntCDC Building. Right: isolated view of part of the MsTBS implementation (Treml, Riedel et al., 2025).

The qualities of the system make it particularly well-suited also for urban densification across diverse building typologies and scales. The potential of which has nevertheless not yet been sufficiently explored.

2. Early-Phase Digital Design Exploration: State of the Art

The conceptual design phase is crucial in influencing a building's sustainability, performance, and life-cycle cost (Bragança et al., 2014), while decisions made in the first 10% of the design process can determine up to 80% of post-construction operational costs (Sharafi et al., 2017). This highlights the importance of computational tools for early-stage architectural and urban design. However, studies reveal that existing decision-support applications often fall short in addressing a wide range of design criteria and stakeholder concerns, often limiting exploration to visual assessments and communicative feedback on pre-defined design (Bruns et al., 2021).

In contrast, interactive, exploratory, and explanatory approaches (Ynnerman et al., 2018), enhanced by visual communication and data-driven storytelling (Carpendale et al., 2021), show promise in extending co-design to decision-making that is architecturally, structurally, regulatively, and socio-culturally informed. This is particularly important for interventions within existing urban environments.

2.1. WEB-BASED ARCHITECTURAL & URBAN DESIGN PLATFORMS

Digital interfaces and gamification approaches are increasingly being integrated into participatory frameworks to enhance stakeholder engagement and understanding of spatial dynamics. These tools support inclusive decision-making and educate users about the complexities of urban systems and sustainable development.

Syte (syte.ms, founded 2021) is an AI-powered platform that performs rapid real estate analyses. Its development potential dashboard provides information on how a site can be maximally utilised in terms of new construction or densification. However, it primarily focuses on exterior site and building boundaries rather than detailed architectural or structural layouts, which are crucial for accurately assessing construction feasibility and guiding comprehensive architectural design exploration.

Infrared.city (Galanos & Chronis, 2022) is an AI-driven urban design platform that makes complex environmental simulations accessible by using pre-trained machine learning models and parametric tools, enabling real-time, data-driven decision-making for architects, planners, and sustainability experts. Users can create simple exterior building volumes and evaluate how design choices dynamically affect performance.

Block'hood and Common'hood (Sanchez, 2015) (Sanchez, 2022), are notable examples that employ gamification to promote ecological design, systemic thinking, social resilience and long-term sustainability. They encourage non-expert audiences to explore the complexities of urban ecosystems, social resilience and collaborative problem-solving, while promoting circular economies and low-waste practices.

SuperBarrio (Markopoulou et al., 2018) is a tool for architects, urban planners and public entities that uses gamification strategies to engage citizens in the design of public space, collect data on their opinions, desires and proposals, and educate them on ways to achieve inclusive and sustainable solutions. Users add elements related to ecology, energy, mobility, and culture, assign functions to vacant buildings, and, as a result,

receive scores based on the positive or negative impact of their interventions.

Lastly, Branch Concept Lite (branch3d.com, 2025) helps architects, engineers, and developers explore multiple structural configurations, experiment with different materials, and receive real-time feedback on key metrics. However, it is limited to grid-based layouts for new multi-storey timber, steel, concrete or hybrid constructions.

3. Aim

Despite the advantages of novel building systems, awareness and access remain limited among key stakeholders. Municipalities, building authorities, housing cooperatives, investors, designers, and citizens often lack the technical knowledge needed to engage effectively with emerging design and construction possibilities. Moreover, there is a notable absence of design exploration tools tailored for extending existing building stock using novel computational MsTBSs and engaging diverse stakeholders.

This study addresses these research gaps by developing novel, exploratory, and integrative computational methods for sustainable urban densification. Specifically, it seeks to unlock the untapped potential of BSEs using the aforementioned IntCDC MsTBS. A further objective is to enhance stakeholder awareness and enable the easy and rapid exploration of multiple design options, while ensuring regulatory compliance in the early design phase. Given urban complexity, adopting a co-design approach that actively involves a broad range of stakeholders, regardless of their prior design or computational expertise, is essential.

4. Methods

To facilitate early-stage participatory design, a digital exploration prototype (Figure 2) was developed that leverages complex computational definitions and real-time

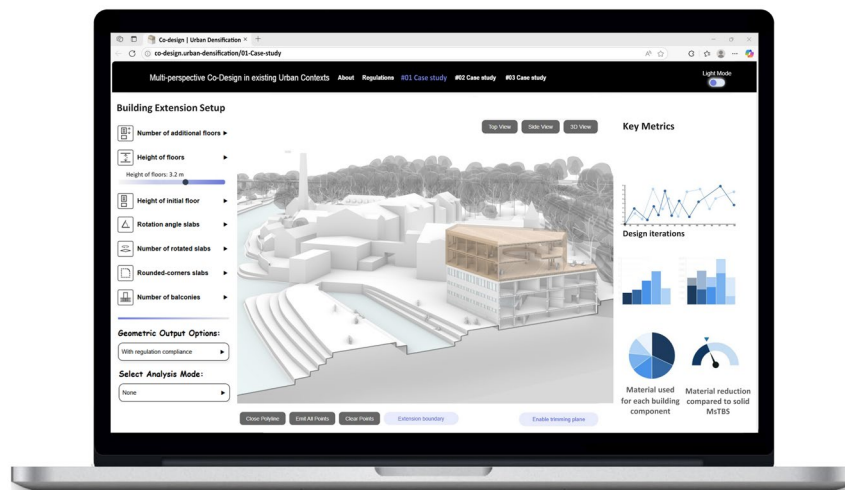


Figure 2. Developed Digital Design Exploration Prototype for sustainable urban densification using the IntCDC MsTBS.

simulations on the web. Innovative visualisation approaches were incorporated to facilitate building stock extensions and urban infills using the IntCDC MsTBS. This approach enables users to apply advanced computational algorithms without requiring scripting expertise or software installation.

The frontend of the browser-based configurator was developed using Vue.js, Three.js, and Node.js. Vue.js was used to implement the interactive user interface, managing user inputs and dynamic configuration parameters, while Three.js enabled real-time 3D visualisation and interaction with the generated building geometries directly in the web browser. Node.js acted as a bridge, handling data exchange between the frontend and the backend services. Regarding the backend, building design methods were created in Grasshopper 3D, integrating custom Python and C# algorithms that encode the geometrical constraints defined by building regulations and the current capabilities of the analysed timber system. Several real-time simulations, including environmental and structural analyses, were incorporated into the Grasshopper environment using Ladybug Tools and Karamba. Rhino.Compute served as the computational solver, executing Grasshopper definitions and processing 3D Rhinoceros models of existing buildings in the cloud. This enabled RhinoCommon functions to be accessed remotely without requiring prior software installation on the user's device. This methodology is illustrated in Figure 3.

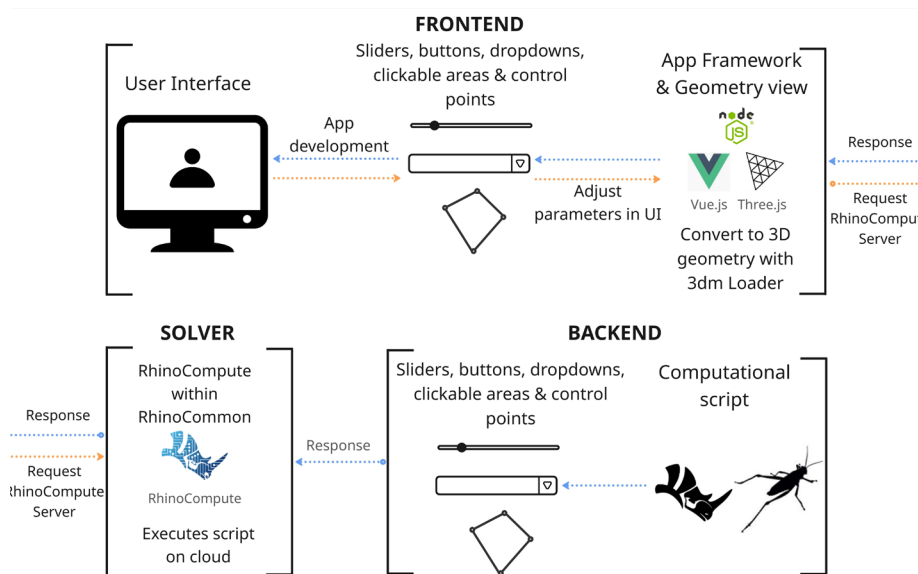


Figure 3. Architecture and data flow in browser-based design configurator

4.1. BACKEND GRASSHOPPER DEFINITIONS

The computational building design methods (CBDMs) embed multiple densification strategies for the massing of vertical, horizontal, and multi-directional extensions. These typologies address three primary categories of existing building contexts: (a) small-scale buildings with regular or irregular footprints; (b) large-scale buildings with

regular or irregular footprints; and (c) urban infill conditions. Each strategy was evaluated in terms of spatial qualities and its potential positive or negative environmental impact on the existing structure and surrounding area. Based on this evaluation, the suitability of each typology was assessed for the three case studies analysed in Section 6. Selected densification approaches were efficiently incorporated into the CBDMs to allow rapid and intuitive design exploration.

The next aspect incorporated into the CBDMs was the integration of geometrical constraints imposed by regulations. To this end, we identified key regulatory criteria specific to the State of Baden Württemberg (Germany) and implemented them into the design tool. A critical advancement was the algorithmic implementation and automation of these constraints, which significantly accelerated their application and enabled rapid iteration across each case study. While building regulations vary internationally, the selected criteria reflect widely recognised conventions commonly used in early-stage urban planning worldwide.

In addition to regulatory constraints, geometric constraints specific to the IntCDC MsTBS were incorporated into the CBDMs. These include limitations on the maximum allowable span between structural elements, such as columns; the maximum cantilever length; and the optimal slab thickness required for effective sound insulation. Integrating these constraints creates a continuous feedback loop between the building system and the architectural design, supporting iterative and system-aware decision-making throughout the design exploration process.

5. Workflow and User Experience

The web application has been designed with a strong focus on improving the user experience. It features a clear visual interface, intuitive controls, interactive 3D navigation, rapid massing iterations, real-time simulations and the ability to compare and download saved densification scenarios.

The workflow for developing a densification scenario begins with identifying existing buildings that are suitable for expansion, and then collecting relevant contextual information. Essential data is gathered for each target building, including architectural layouts, structural elements and capacities, circulation zones (stairs and elevators) and wet areas (bathrooms and kitchens). This is then supplemented with information on the broader urban environment, such as green and blue infrastructure, public transport, building typologies and uses, as well as heritage structures. This initial data preparation, particularly with regard to the target buildings and the detailed surrounding building volumes, is carried out prior to user engagement due to the current limited availability of well-structured, open-source data for the analysed region.

Once the preliminary data has been prepared, users can engage with the online configurator to explore different densification scenarios. They can shape proposed extensions by defining boundaries for the footprint, voids, balconies and roof shapes, as well as the intended use. They also have the option to either design within regulatory constraints that must be considered during the early design phase, or to explore unconstrained design possibilities.

Throughout the design process, users benefit from interactive exploration. They can refine the design iteratively based on real-time feedback, revisiting steps until they are

satisfied. They can also save and compare multiple design iterations, evaluating each one against key metrics in a manner similar to Design Explorer (Thornton Tomasetti, 2019). For further analysis or optimisation outside the web environment, users can export parameter values in .csv format and 3D models in .3dm format.

6. Case Studies and Results

Following the development of the CBDMs, we selected three case studies in Baden Württemberg (Figure 4) to evaluate both their applicability and the usability of the browser-based design tool. Two of the selected cases are situated in urban contexts, while the third is located in a suburban environment. These case studies showcase a diverse range of typologies, construction years, scales, ownerships and site contexts, and demonstrate seven potential extensions to existing buildings (see figure 4, labelled a–g). The buildings also vary in shape, size, structural and geometric layouts, and programmatic functions. They differ further in span lengths, number of stories, presence or absence of voids and cantilevers, and building materials.

The results from all three case studies demonstrate the system's versatility. It successfully achieved long, multiaxial spans of up to 11 metres and cantilevers extending up to 2.5 metres. These capabilities enabled the generation of diverse architectural features, including differently shaped voids, overhangs, and balconies, without the need for external supports. This confirms the tool's effectiveness across diverse building typologies and contexts. Conditions in which slab boundaries are located in very close proximity to structural point supports require further investigation.

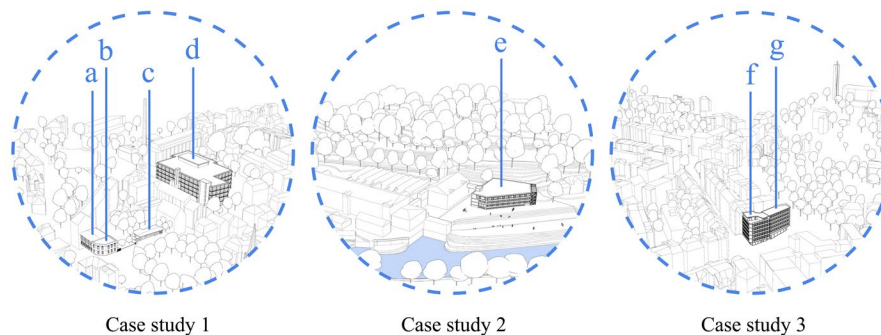


Figure 4. Selected case studies in Baden Württemberg

7. Discussion and Outlook

This paper focuses on the development and testing of exploratory building design methods for applying the IntCDC MsTBS to building stock extensions (Figure 5). The findings demonstrate that the system's inherent geometric flexibility and adaptability enable it to support sustainable and socially conscious design solutions.

The data-driven, exploratory and participatory approach raises awareness among stakeholders, allowing them to actively contribute to design decisions, develop regenerative solutions, and engage with novel computational building systems and design methods. These innovations open up significant opportunities and outline a

promising path for the continued evolution of the AEC industry. They contribute to the refinement of existing building systems and the development of new ones, guided by the evolving needs for resilient, adaptable, and human-centred urban environments.

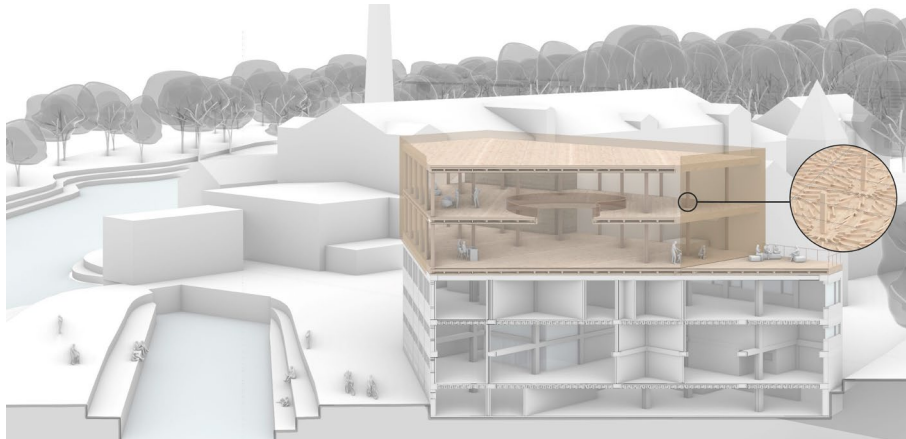


Figure 5. Building stock extension using the IntCDC MsTBS (Case Study 2).

The lack of open-source, well-structured information, especially regarding the architectural and structural layouts of existing buildings, necessitates the preparation of data prior to user participation and design exploration. Finally, future user studies involving various stakeholders will provide valuable insights through the systematic evaluation of feedback on the building system, and the usability, intuitiveness and effectiveness of the digital design configurator. These studies could also identify stakeholder design preferences and decision-making criteria, as well as areas of contention. They might also reveal new typologies for extensions to existing buildings.

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