WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

CIRCULAR DESIGN FOR URBAN DENSIFICATION THROUGH EXTENSION CONSTRUCTION

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ABSTRACT: In order to accommodate increasingly high populations and preserve urban green areas, the strategy of urban densification has led to the rise of vertical architecture expansion. At the same time, residential buildings constructed in the 20th century are confronted with the dilemma of outdated equipment that fails to meet the needs of contemporary usage. In costly neighbourhoods, retrofitting is preferable to demolition for cultural and economic development. This study will use volumetric timber modules which have the potential to be reused, resulting in a sustainable retrofit solution. Simultaneously, factory production of modular products enhances manufacturing accuracy and on-site assembly efficiency, substantially minimising the impact of the construction period on the surrounding area of the renovation project. Subsequently, three functional modules will be introduced to produce various design outcomes that simulate different expansion strategies. The research takes into account the design constraints given by various expansion directions and functional requirements in order to assess the feasibility of the extension outcomes. The discussion will focus on the application of modular timber products to realise a circular retrofit building, consequently contributing to the relevant field.

KEYWORDS: modular timber construction, combinatorial design, vertical extension, sustainable retrofitting.

1 – INTRODUCTION

In light of changing urban demographics and shifting building functions, such as a shortage of available urban housing and a requirement to renovate antiquated infrastructure, sustainable building renovation remains one of the issues of concern to be addressed [1, 2]. Modular solutions reduce overall project costs by replicating products compared to customised designs, resulting in shorter time schedules and durations [3, 4].

As a result, modular construction has a short assembly period, which minimises disturbance to building tenants and adjacent buildings, as well as surrounding traffic, throughout the renovation phase. In addition, given the limitations of the existing structure, load-bearing capacity is a crucial factor for extension tasks, and the lightweight characteristic of timber modules is one of the reasons for the choice in scenarios where the foundations possess adequate structural reserve capacity for an extension. However, there is a lack of conclusive research on the design process of three-dimensional (3D) timber modules in renovation and extension projects. A study of combinatorial circular design for modular products could enhance the decision-making process and offer a more empirical approach for future work.

The renovation of buildings is essential to alleviate urban densification. Demolition and retrofit are completely distinct options. Vandkunsten’s Life Cycle Assessment (LCA) analysis shows that in the worst-case scenario, the demolition of concrete apartments and the subsequent construction of a new building is about 300 percent more damaging to the climate than the renovation of an existing building [5]. The renovation approach can only enhance the living conditions, the interior layout is still constrained by the original design. According to the report conducted by Cronhjort et al. [6], the majority of

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https://doi.org/10.52202/080513-0293

dwellings constructed prior to the 1970s were designed as three-room "standard-family" residences.

A survey of the Copenhagen housing market found that young individuals and small families show the highest demand for apartments measuring up to 60 square metres [7]. Consequently, the design of expansive apartments may not satisfy the current demand for housing, particularly for units including 1–2 bedrooms, which are in limited supply in urban areas. The study conducted by Graham et al [8] proposes a sufficiency-oriented housing solution, where tenants should consider the sizes and distribution of housing concerning space utilisation and energy efficiency, as household size and home usage efficiency change over time.

Modular room extensions for retrofitting enable the addition of spatial modules that can either change or match the original usage function. For instance, in an existing residential building in a city centre, the addition could be designed as a workspace. Existing structures may be revitalised by the construction of modular extensions. Extension spaces can be both economical and sustainable because of their architectural flexibility and functional diversity.

Over the past two decades, expansions have become a prevalent method of construction. FlexModul A/S expanded an existing office with th 3D timber modules. The original structure was added by three more storeys, with the same dimensions and materials [9]. The Solna Hotel in Sweden was expanded utilising timber components with wood–aluminium–glass facade systems. The additional area is situated above the existing conference hall [10]. The majority of structures built in the previous century requiring renovation were constructed of masonry or concrete. Cronhjort et al. [6] developed a timber-based element system (TES) for the façade to ensure compatibility of the extension modules with the various structural systems of the existing building. In addition to focusing only on the technical feasibility of the existing retrofit, Choi and Kim [11] provide a quantitative evaluation tool to conduct a deep renovation feasibility analysis for the extension project using a calculated benefit-cost ratio.

This paper starts with an introduction to the basic principles of extension operations. It then discusses the extension strategies for vertical, horizontal, and multi-directional extensions. Subsequently, different functional modules for combinatorial design are introduced. Following that, the Python-based WASP tool, a Grasshopper plugin for design simulation, was introduced. In the results section, the socio-habitat effects of different extension designs on the surroundings will be thoroughly analysed. The design of facades and the evacuation area between the extension and the original structure will be investigated. The influence of the design of added timber modules on potential reuse strategies will be explored. The results will provide significant insights into the development of research and industrial practices across various fields.

2 – METHODOLOGY

This section highlights the principles of an extension strategy based on existing building, environmental, and construction constraints. The various types of extension modules, together with their functionalities and usage constraints, are defined. The WASP Grasshopper plugin is introduced to explain the stochastic aggregation approach for volumetric timber modules.

2.1 The principle of extension

Extensions are often considered as new constructions and thus must be constructed to comply with the legal standards for new buildings, including fire safety, accessibility design, sound and heat insulation and urban planning requirements. The methodology for extensions can significantly differ based on the situation of the existing structure. Besides, the influence on neighbourhood connection and tenants in the current building must be considered while designing an additional area. Thus, the principles of extensions will be classified into three categories: vertical extensions, horizontal extensions, and multi-directional extensions.

Fig. 1 depicts *Approach 1* to extension, which is to create more space along the vertical of the existing building. The building is usually designed to be expanded by adding roof-level storeys. This is the most common method of extension, and the lightweight construction components can be easily mounted on the existing structure. This strategy enhances land space utilisation while preserving adjacent ground areas that may lack extension approval. At the same time, utilising the current heating and cooling systems of the existing structure can make vertical extensions cost-effective by diminishing utility expenses per square metre. The limitations include the structural capacity of the foundations and existing floors, and the current solution is to transfer loads through the original structure or within the new building envelope. In vertical extensions, the evacuation route can be positioned outside the existing

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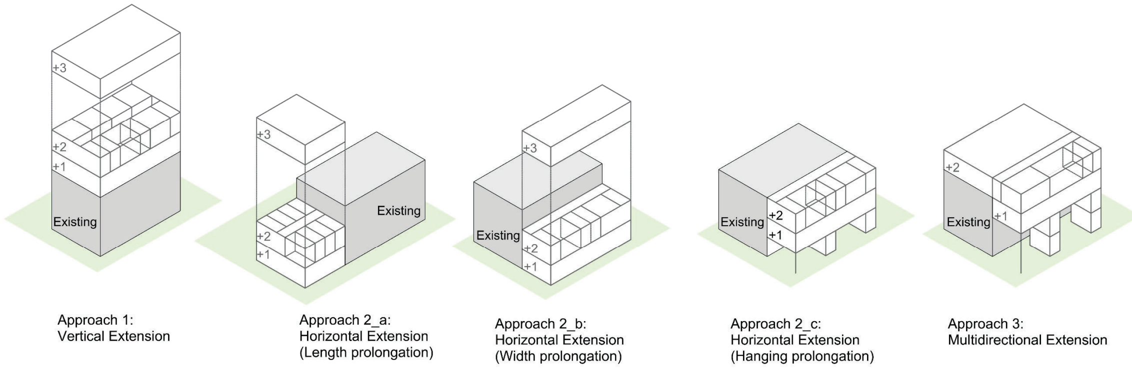

Figure 1. Approaches to sustainable retrofitting using volume timber modules.

structure, thereby raising the expenses associated with supplementary lifts.

Horizontal extensions can be developed when the current construction capacity is insufficient for a vertical extension and the surrounding region is allowable for usage. *Approach 2_a* in Fig. 1 prolongs the existing structure, permitting its construction independently from the current building. In contrast, *Approach 2_b* expands the width of the current structure. This solution typically involves an extension that serves as an alternative evacuation path, e.g. a balcony area, ensuring that natural light remains unhindered. However, if an enclosed extension is desired, the hanging *Approach 2_c* can be used with only a portion of the building's facade obscured from view. This must be evaluated in each case individually. The benefits of the horizontal expansion strategy include reduced construction complexity and easier access to construction permits. However, the drawbacks include increased land costs, environmental effects, and utility expenses per square metre.

Combining the aforementioned strategies, *Approach 3* presents an extended option address in both vertical and horizontal directions. The Fjaeldevænget building example in Aarhus, Denmark, indicates that simultaneous vertical and horizontal roof extensions are feasible. The horizontally extended stairwells and overhanging aisles serve as a linkage to adjacent buildings, providing supplementary evacuation space for residents in the extension region [12]. This multi-directional construction method brings together the benefits and drawbacks of the vertical and horizontal extension categories, although it requires customised analysis within the situation of the existing structure.

2.2 Extension modules

In this paper, the three different modules are set as the discrete elements for aggregation process generation. The design data of modular units was obtained from a prior investigation of volumetric timber module dimensions in real-life projects [13]. Fig. 2 illustrates that the dimensions of the room and staircase modules were determined as 3 m (width) × 3 m (height) × 6 m (length). The dimensions of the corridor module have been set as 1.5 m (width) × 3 m (height) × 3 m (length). Since the longitudinal direction of the corridor module is intended to be parallel to the width direction of the other two modules, the length of the corridor is equal to the width of the other two modules.

The walls in the width direction of the room module were constructed with different openings to imitate entry and window configurations. The staircase module only has a door as an entrance on one side of the short-oriented wall, while the remaining three vertical walls are enclosed. To simplify the connection rules for the subsequent phase,

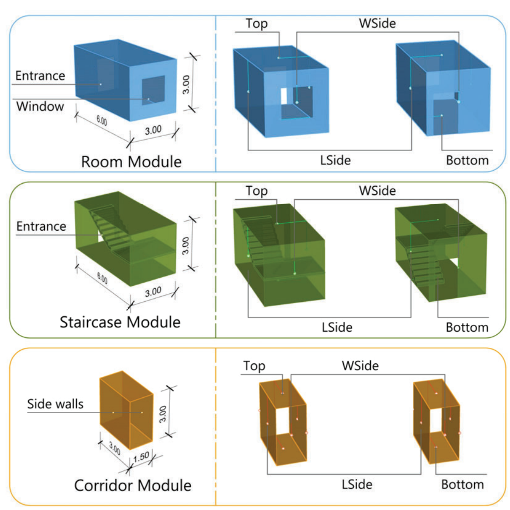

Figure 2. Dimensions and reference information for extension modules.

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the visualisation of vertical passageways in both the top and bottom floor slabs of the staircase module is hereby simplified. The corridor module is consisted of four walls. Although the vertical walls on both sides are presented to simulate the connections in the step, this does not imply that they are used as solid walls in this module. Furthermore, the names of the module's six sides are given, and they have been divided into four categories: "Top", "Bottom", "Long Side" (LSide), and "Wide Side" (WSide). Connection nodes and reference lines on either side will allow the integration of different modular items with the WASP tool.

2.3 Customised algorithm in wasp

WASP is a Grasshopper plugin created with Python scripting to offer combinatorial tools for the design of discrete elements [14]. The user may customise the connection settings and constraints for the generated design. The connection rules in this work are defined as aggregations between units based on a realistic combinatorial layout, as shown in Fig. 3 below.

Group 1 illustrates the connections between two staircase modules, which are configured to allow connection only between the floor and ceiling for vertical access.

In Group 2, corridor modules can be vertically attached to simulate the design of different floors, and in Group 3, wall connections can be utilised to represent the three sorts of linkages on the same floor. The room modules have been defined to be connected only side by side along their longitudinal direction, indicating that entrances and windows must remain unconnected and hence not be concealed.

In Group 4, the integration of the stair and room modules is shown, following the principle of preventing the arrangement of openings in the side walls. Groups 5 and 6 demonstrate the linkage of the corridor module to the room module and the staircase module, respectively. Group 6 has three additional options compared to Group 5, as the staircase module contains three vertical walls available for connections to other modules, while the room module has just two walls chosen for connections.

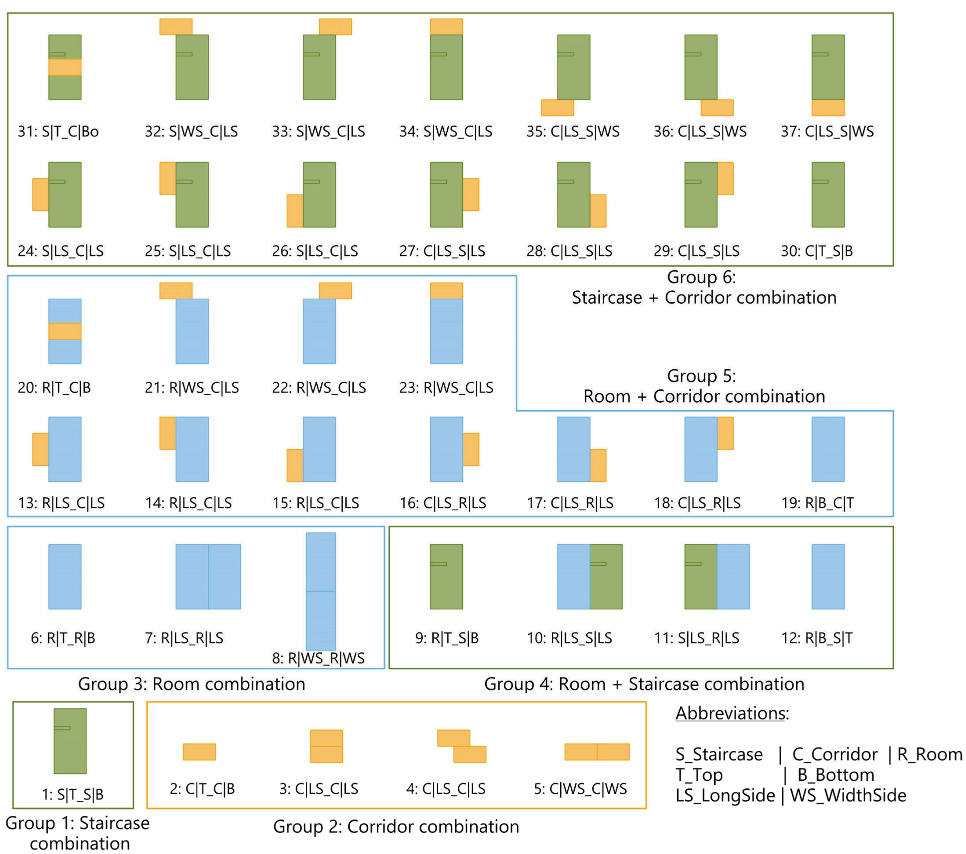

Figure 3. Connection rules for extension modules in WASP.

This note describes the different module functions and their connection surface abbreviations. On the basis of these connection settings, further details and various connection conditions can be added. Given that the focus of this paper is to explore the possibilities of expanding on the existing buildings. The established principles are therefore based on the functionality of the modules and the most common layout design in practical applications.

In addition to the connection configuration, global-level constraints were set up to improve the modelling of extensions to existing buildings. It serves to construct the current structure within spatial boundaries, denoting the permissible expansion area used to place the expansion module. The external surfaces of the existing building have been defined as “hard” constraint surfaces. The extension area was determined to include the two stories above the roof and the side extensions measuring 7.5 m which could comprise a room unit (6 m in length) and a corridor unit (1.5 m in width).

3 – ANALYSIS

This section analyses three extension methods and describes the configuration of the modules. The provided designs will be utilised to investigate the influence of the extension timber modules on the elevation and evacuation design. The influence of the extension to the adjacent area will also be considered. An evaluation of the generated combinatorial design concerning prospective reuse strategies is also covered. In all cases, the existing project was designed as a four-storey building with an indeterminate structural form. The building has a floor height of 3 m and a roof area measuring 30 m in length and 13.5 m in width.

3.1 Vertical extension

As shown in Fig. 4, the vertical extension design was developed using 18 room modules, 10 corridor modules, and 2 staircase modules based on the various functional volumetric construction units described in the Methodology section.

In terms of construction layout, Extension scheme I in Fig. 4 is a typical vertical extension example. Each room module is positioned adjacent to the neighbouring rooms, with the extended space aligned with the outer boundaries of the current building. The evacuation design depends significantly on the design characteristics of the existing structure, specifically whether the quantity and dimensions of access routes from the top level to the roof comply with the renovation requirements. The evacuation unit can be constructed as an independent part external to the building to serve people utilising the additional area separately.

The second layout, shown as Extension scheme II in Fig. 4, is generated under identical conditions, utilising the same quantity of different functional modules as Extension scheme I, and complying with the customised WASP connection rules. The vertical extension is a two-storey design. All corridor and staircase modules are situated on the first expansion storey, while the other room modules are placed in the second storey area following the spatial constraints. In contrast to typical practical layouts, the aggregation offers a variety of living units. The floor layout indicates that areas including 2 to 5 room modules can accommodate various occupant sizes. The option of two-story flats is also available. The non-alignment of the façade walls in the

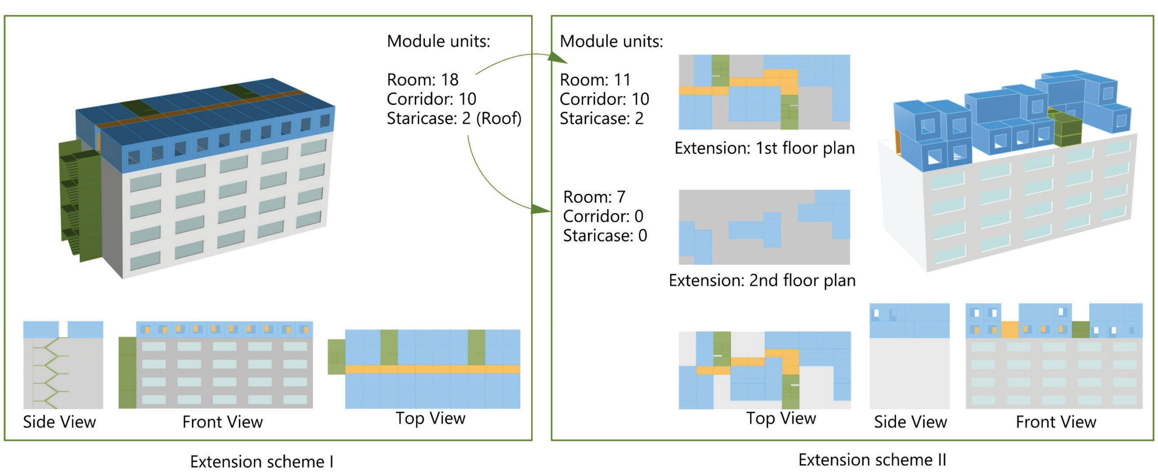

Figure 4. Common layout and ‘rooftop community’ result in vertical extension approaches.

https://doi.org/10.52202/080513-0293

extension area and the withdrawal of the room modules from the existing building edge create outdoor space for those who live in the extension area. The specified region can serve as either a common space or a private yard for each rental home. Currently, the common target group for rentals in the extension area is the group of 1–2 tenants. In the layout presented in this work, the combinatorial design creates a “rooftop community” for the building. This therefore increases the appeal for family-sized residents. Moreover, the flexible layout design built by the modular units has the potential for variability, enabling the circularity of both the extended modules and the pre-existing building.

According to the specifications of the expansion plan, the requirement for the extension to align with the façade design of the existing structure could serve as a constraint. The vertical direction of the extension will minimally affect the indoor environment (daylight) conditions for the residents of the existing structure. The influence on adjacent structures must be evaluated using distinct calculations of relevant data, which is a crucial criterion for securing planning approval for vertical extensions.

3.2 Horizontal extension

Horizontal extension strategies significantly affect surrounding land and current building tenants. Therefore, horizontal extensions are classified into four scenarios as illustrated in Fig. 5. The initial scenario is the prolongation of the building, depicted as Horizontal extension_a. The addition can be built as an independent structure, thereby minimising the living environmental impact on existing structures. The evacuation module links the individual room modules in the extension structure. Access between the extension and the existing building may also be achieved by using large openings in the side walls of the existing building. However, for projects located in urban centres, the land area needed for expansion is not easily obtainable, which is intricately related to the development planning for the areas surrounding the building.

If the expansion is constructed along the original building’s facade, light and views for residents are crucial. A typical building strategy for width prolongation consists of corridor or balcony modules, as illustrated in Fig. 5, Horizontal extension_b. However, the installation of room modules at the front of the building will block daylight to the existing structure. A potential option is to place room modules on the outside of the lower stories, as seen in Fig. 5, Horizontal extension_c, therefore avoiding the impact on the residents of the upper floors. The chosen extension facade relates to a region inside the structure, either a room area or a functional zone. The design aims to utilise extension modules to enlarge the interior area via wide window openings and minimise its

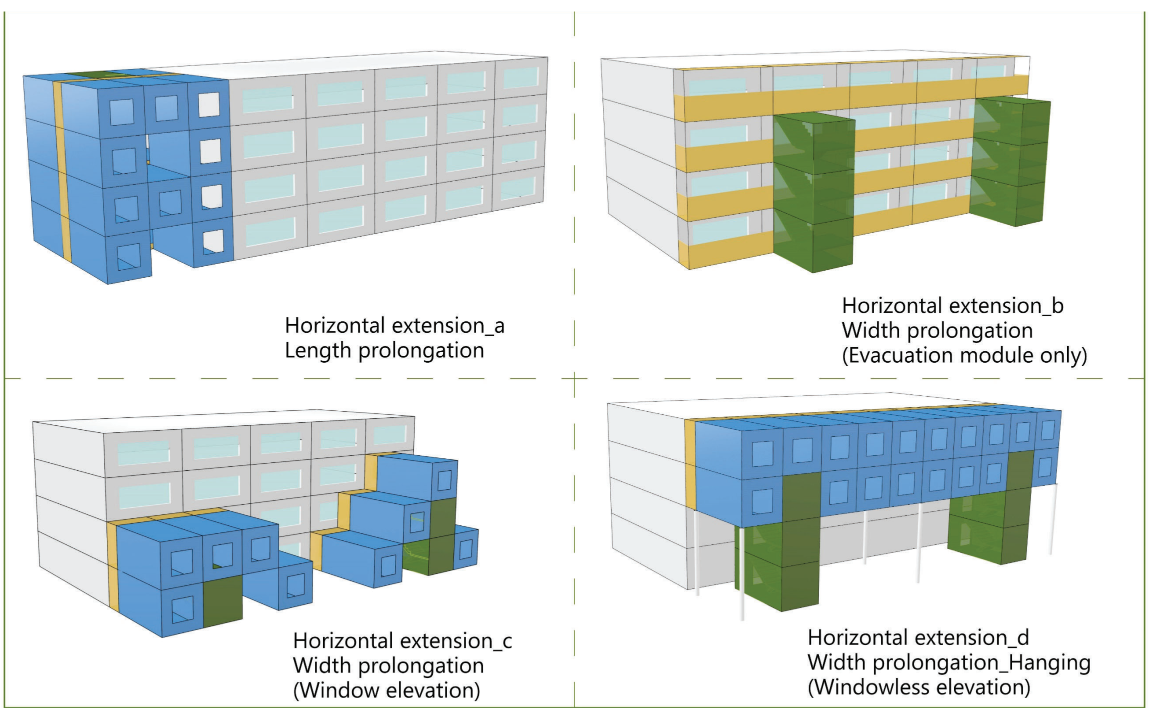

Figure 5. Horizontal prolongation of the existing system.

impact on the interior environment. This situation is the most complicated, requiring a more detailed investigation of feasibility.

There exists a scenario in which the extension is constructed with overhangs. The room modules were attached to the existing structure and are supported by an extra vertical structure. This method considers the limitations imposed by the land use licence. The projection area applicable to the extension is to be reserved for public use and cannot be occupied. This approach allows the extension along both the length and width of the current building. As seen in Fig. 5, Horizontal extension_d, an extension may be positioned in the back of the building, where poorer views and diminished sunlight typically serve as orientation for the bathrooms and stairwells.

3.3 Multi-directional extension

Based on the two aforementioned extensions, Fig. 6 illustrates the third study scenario, which combines the previous design criteria. The pink-highlighted area functions as a constraint-space condition for WASP to produce aggregation results. Given that the extension space exceeds the roof area, a vertical evacuation path is also an essential design condition for using this strategy. Therefore, a staircase is placed beneath the overhanging section. According to these additional constraints, the extension method can provide a multidirectional extension of the construction.

An extension in the height and width directions, as shown in Fig. 6, Multidirectional extension_a, is an effective way to combine the utilisation of large areas of roof space with floor area savings. As for the vertical height and building length extension options, the hanging part can be used as a passageway connecting the vertical extensions of the existing structure. To demonstrate the practicality of this approach, the structure shown in Fig. 6, Multidirectional extension_b, is a pilot renovation project called Gellerup blok B4, located in Brabrand, west of Aarhus [15]. The current structure was built in the 1960s as welfare housing. In accordance with the road access plan, it preserves the integrity of the entire neighbourhood. A side support wall was built outside of the existing structure, and a new three-storey structure with a separate stair/lift tower was constructed rising from the road access. The design aimed to resolve the problems related to the closure of the entrance area and the transition at the ground level.

4 – DISCUSSION

Extensions could give a renewed opportunity for revitalisation of an existing building. Volumetric timber modules were chosen for the study because of their design advantages of being lightweight and adaptable. Previous research on extension approaches indicates that additional relevant topics need further discussion to facilitate applicability.

The proposed "rooftop community" concept can address the issue of limited housing type options in vertical extensions. The number of limited uses for each functional module in the WASP aggregating tool could produce hundreds of different outputs based on the given customised connection criteria. The problematic configuration of the corridor and staircase modules'

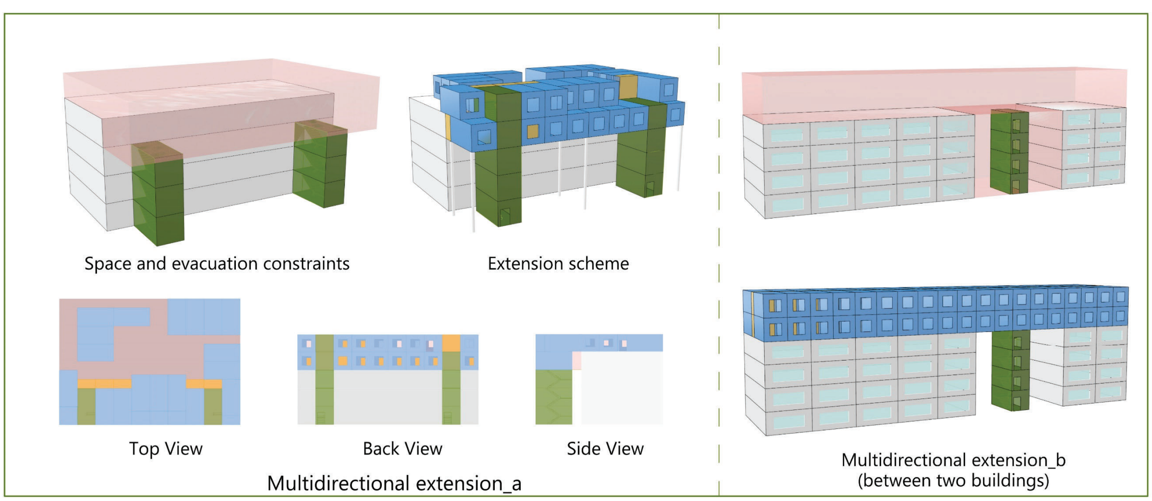

Figure 6. Multi-directional extension of the existing system.

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entrances face to the roof's edges as well as the lack of public connecting areas between the room modules are factors in human screening. However, additional design constraints related to practical applications require analysis. The other two approaches, horizontal expansion and multi-directional extension require the utilisation of additional land area. Evaluating feasibility and securing approvals is far more complicated than the vertical extension method. The potential for using these two solutions remains significant, as extensions enable not only to increase living density but also to substantially improve the living conditions of current residents. Horizontally extended room modules enhance internal lighting conditions and enlarge space in small apartments. This is essential in regions with higher housing demand in major urban centres.

In addition to considering the appropriate layout of extension modules, construction may be a greater challenge. The most difficult technical issues are how to consider the load-bearing capacity of the additional components and meet the design criteria for different load conditions, as structural modifications to the roof structure and external walls must not undermine the existing building's load-bearing properties. In addition to structural stability, the way the extension is built must be considered in terms of its impact on the original building, such as vertical extensions that use the existing building's equipment pipework or changes to the living conditions of residents on the top floors as a result of roof reconstruction. In addition to the structural relationship with the original building, the extension area's utilisation of timber modules was intended to achieve the design objective of circularity. Consequently, the connections between the modules for dismantling and reassembling were also essential.

5 – CONCLUSION

The study aims to promote the application of sustainable renovation methods. The research findings could enable the expansion of living spaces, improve interior living conditions, and prevent building demolition by transformative renovation. The study investigates ways of expanding space through volumetric timber modules and explores the layout of these modules to enhance design adaptability.

The Grasshopper plugin WASP was utilised as an aggregation design tool to present the outcomes. Three different functional modules were created to accurately represent practical applications and to increase comprehension of the layout requirements. Customised connection settings facilitated the logical layout of the various modules, allowing for diverse combinations. Applying spatial and evacuation constraints throughout the design phase enhanced the feasibility of the research findings.

In addition to the consequences discussed in this work, there are numerous more factors to take into account throughout the design phase. Structural load-bearing capacity, land use licenses, fire regulations, and environmental design are all critical variables for further study. Although this study only presents a layout study for the expansion area, the proposed design strategy for the combination of wood modules has the potential to provide valuable insights for future studies that are based on other influencing factors.

6 – ACKNOWLEDGEMENT

The first author gratefully acknowledges the financial support for living expenses provided by the China Scholarship Council (Grant No. 202209110036) and a conference grant from the Department of Civil and Architectural Engineering, Aarhus University and the William Demant Fonden. The remaining authors wish to thank EU Interreg ÖKS for financial support via the project ASCEND.

7 – CONTRIBUTIONS

Jiayi Kayee Li: Conceptualization, Methodology, Software, Investigation, Illustration, Writing—original draft. **Lars Vabbersgaard Andersen**: Conceptualization, Methodology, Writing—review and editing, Supervision. **Markus Matthias Hudert**: Conceptualization, Methodology, Writing—review and editing, Supervision.

All authors have read and agreed to the published version of the manuscript.

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