

Vertical Extensions of Post-War Housing Estates: Comparative Analysis of Existing Projects and Design Space Exploration Using the IntCDC Multi-Storey Timber Construction System

Maria PAPADIMITRAKI^{a,c*}, Lorenz RIEDEL^{b,c}, Hans Jakob WAGNER^{a,c}, Jan KNIPPERS^{b,c},
Achim MENGES^{a,c}

^{* a} Institute for Computational Design and Construction (ICD), University of Stuttgart
Keplerstraße 11, 70174 Stuttgart, Germany
maria.papadimitraki@icd.uni-stuttgart.de

^b Institute of Building Structures and Structural Design (ITKE), University of Stuttgart

^c Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC),
University of Stuttgart

Abstract

This study examines sustainable densification strategies for post-war housing estates, with a particular focus on vertical extensions. Twenty realized projects in the DACH region (Germany, Austria, and Switzerland) are reviewed alongside existing literature on design strategies and structural systems for such interventions. One case study is selected for an in-depth analysis to inform the exploration of alternative design approaches. A point-supported, multi-story timber building system (MsTBS), currently used in new construction and characterized by high spatial flexibility, is introduced as an alternative to conventional structural solutions for building stock extensions. Based on this system, a new intervention is developed that addresses three key challenges commonly associated with densifying post-war housing estates. Structural simulations are carried out using Karamba3D and SOFiSTiK within an automated Rhino/Grasshopper framework to enable preliminary dimensioning and feasibility assessment. In parallel, environmental performance is evaluated using Ladybug Tools to inform environmentally responsive design decisions in the early design stages. The review of realized densification projects reveals a clear trend toward enhancing sustainability and social inclusion. The MsTBS has proven particularly well-suited to accommodating diverse structural and architectural requirements, while enabling flexible floor plans and material-efficient construction.

Keywords: post-war housing estates, sustainable urban densification, vertical and horizontal building extensions, adaptive timber building systems, computational design, design freedom

1. Introduction

Post-war housing estates emerged as a key response to the acute housing shortages following World War II. Their rapidly deployable, cost-efficient, and resource-conscious construction methods enabled the swift provision of large quantities of housing. At the same time, prevailing urban planning paradigms emphasized access to daylight, natural ventilation, and generous green open spaces, alongside a clear separation of functions and land uses. As a result, new residential developments were typically located on the peripheries of historically evolved cities and characterized by relatively low densities, with floor space ratios (FSR) ranging from 1.0 to 1.2 [1]. In Germany, these developments were further shaped by the Federal Land Use Ordinance (BauNVO), introduced in 1962, which established strict limits on building density. In contrast, inner-city areas were largely reconstructed at their original, and significantly higher, densities, often exceeding an FSR of 2.5 [1].

However, the predominantly quantitative understanding of density underlying these developments neglected the broader social and cultural dimensions of urban life. Consequently, many of these modern yet weakly urbanized neighborhoods were soon criticized for their limited livability. Over time, further challenges have become evident, including aging infrastructure, inadequate insulation, poor energy performance, and restricted accessibility. In addition, many estates have underutilized open spaces, repetitive building typologies, inflexible apartment layouts, and patterns of social segregation.

Despite these shortcomings, the architectural language of post-war housing, characterized by simplicity, functional rationality, and low building density, continues to shape the urban fabric of cities worldwide. In Germany, for example, multi-family residential buildings constructed between 1950 and 1989 constitute the major share of the current urban housing stock and offer significant potential for vertical extension [2]. In particular, the relatively shallow building depths make them well-suited for additional stories. From an energy efficiency perspective, the addition of a new storey to the top of an existing building can reduce heating demand by up to 50% [3]. This reduction is primarily achieved by replacing the existing roof with a highly insulated construction, thereby significantly decreasing heat losses. At the same time, average living space per capita has increased substantially, rising from approximately 15 m² in 1950 to 49.2 m² in 2024 (Figure 1). This development calls for a critical reassessment of conventional density metrics as well as contemporary housing models and apartment layouts.

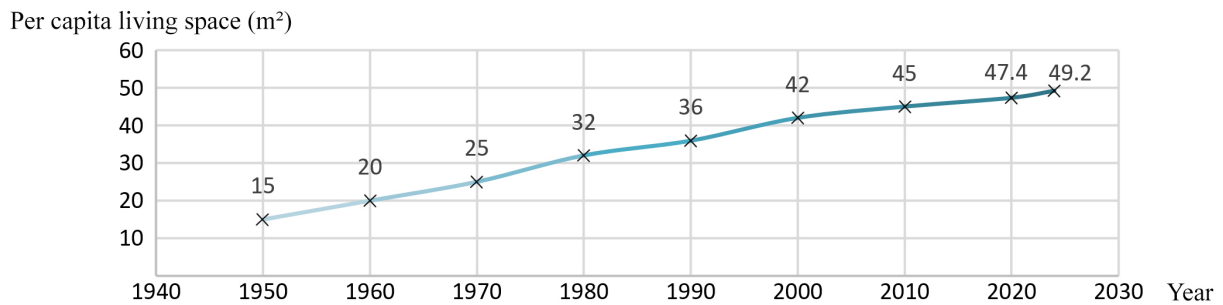


Figure 1: Development of per capita living space in Germany between 1950 and 2024, based on data from sources [1] and [4].

In light of growing housing demand, evolving household structures, land scarcity, and the urgent need for sustainable and resource-efficient urban transformation, the revitalization and densification of post-war housing estates have gained renewed attention. Within this context, vertical extension strategies have emerged as a promising approach for increasing housing capacity while enhancing the spatial and architectural quality of existing building stock without consuming additional greenfield land. Nevertheless, despite their potential, large-scale implementation remains rare beyond a few flagship projects.

2. Case studies

Twenty housing estate densification projects in the DACH region were selected based on literature and digital sources, including both academic and general publications. The selection criteria focused on post-war housing estates that implemented vertical and horizontal extensions using timber or timber-hybrid construction and for which sufficient documentation on both the existing housing estate and the densification intervention was available. Ten case studies were selected in Germany, five in Austria, and five in Switzerland.

Data were collected on the estate's location, the architectural office responsible for both the original and the densification design, construction year and methods, materials used for existing buildings and extensions, as well as the load-distribution method. Further parameters included the number of buildings and stories, apartment typologies, floor area ratio, site coverage ratio, and density factor, as well as provisions for barrier-free accessibility. Additional aspects considered included the legibility of the additional structures and cantilever lengths, where applicable. All data were compiled into a table [5] and were progressively supplemented as new insights emerged.

3. Comparative analysis

A comparative analysis (Table 1) of the selected housing estates was conducted to evaluate the characteristics and extent of their transformation. The estates are classified into five categories addressing architectural, structural, environmental, and social strategies. The framework provides a systematic evaluation of densification interventions by examining architectural qualities, structural approaches, floor plans adaptability, environmental performance, and social inclusion.

Table 1: Comparative analysis of twenty housing estate densification case studies in the DACH region.
The classification legend is shown above.

Case study	Project name	Country	City	Intervention Legibility	Construction material	Floor plan strategy	Environmental Sustainability	Social Inclusion
1	Ziekowkiez	Germany	Berlin	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
2	Fernpassstraße	Germany	Cologne	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
3	Piccoloministraße	Germany	Cologne	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
4	Fritz-Kissel-Siedlung	Germany	Frankfurt a.M.	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
5	Platensiedlung	Germany	Frankfurt a.M.	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
6	Bebelallee	Germany	Hamburg	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
7	Heilbronnerstraße	Germany	Karlsruhe	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
8	Attenkoferstraße	Germany	Munich	● / ● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
9	Fernpassstraße	Germany	Munich	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
10	Gotteszellerstraße	Germany	Munich	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
11	Hauptstraße	Austria	Kierling	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
12	Friedrich-Inhauser-Straße	Austria	Salzburg	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
13	Autokaderstraße	Austria	Vienna	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
14	Gregorygasse	Austria	Vienna	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
15	Maroltingergasse	Austria	Vienna	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
16	Unterdorfstrasse	Switzerland	Bern	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
17	Avenue Wendt	Switzerland	Geneva	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
18	Chemin Aimé Steinlen	Switzerland	Lausanne	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
19	Manessessstraße	Switzerland	Zurich	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
20	Wohnhäuser «Irchel»	Switzerland	Zurich	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●

Legend

Legibility	Readable	● ● ●	Collaged	● ● ●	Hidden	● ● ●
Construction material	Timber	● ● ●	Hybrid	● ● ●	Mineral-based	● ● ●
Floor-plan strategies	Flexible	● ● ●	Supplementing	● ● ●	Preserving	● ● ●
Sustainability	High	● ● ●	Medium	● ● ●	Low	● ● ●
Inclusion	Inclusive	● ● ●	Partially inclusive	● ● ●	Exclusive	● ● ●

Interventions are classified according to their architectural legibility. Additional structures are categorized as (a) readable, (b) collaged or (c) hidden, depending on how clearly new stories or volumes can be distinguished from existing buildings. In terms of construction material, additions are identified as (a) timber, (b) hybrid or (c) mineral-based. These categories indicate whether the extensions are predominantly timber-based, combine timber with mineral-based materials, or rely primarily on inorganic materials such as steel, concrete, or masonry. Floor plan strategies are classified as (a) flexible, (b) supplementing or (c) preserving, depending on whether apartment layouts are largely retained, modestly adapted, or fundamentally reconfigured to allow for different typologies and uses. From an environmental perspective, the case studies are assessed on a scale of (a) high, (b) medium and (c) low environmental sustainability, based on criteria such as embodied carbon and passive house strategy implementation. In terms of social inclusion, the design is categorized as (a) inclusive, (b) partially inclusive or (c) exclusive, indicating the extent to which it

incorporates provisions for barrier-free access, adaptable and multigenerational apartment types, mixed-income, and mixed-use programs. Finally, two cross-category correlations are examined: (1) floor plan strategy and social inclusion, considering how spatial flexibility correlates with accessibility and social inclusion (Figure 2); and (2) construction material and environmental sustainability, relating construction methods and materials to environmental performance (Figure 3).

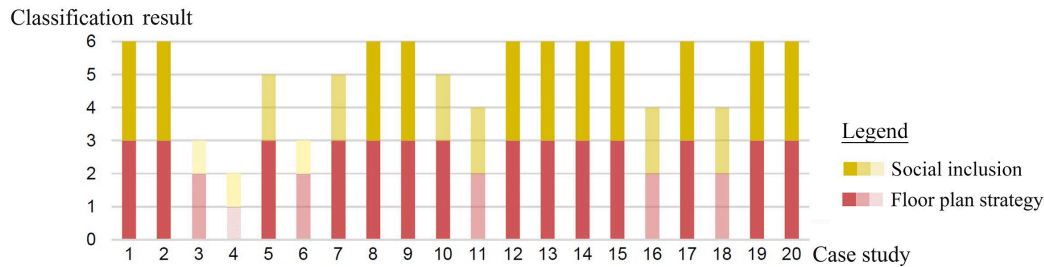


Figure 2: Stacked bar chart illustrating floor plan strategies and levels of social inclusion across the twenty analyzed case studies. Darker tones indicate a greater variety of floor plans and a higher level of social inclusion.

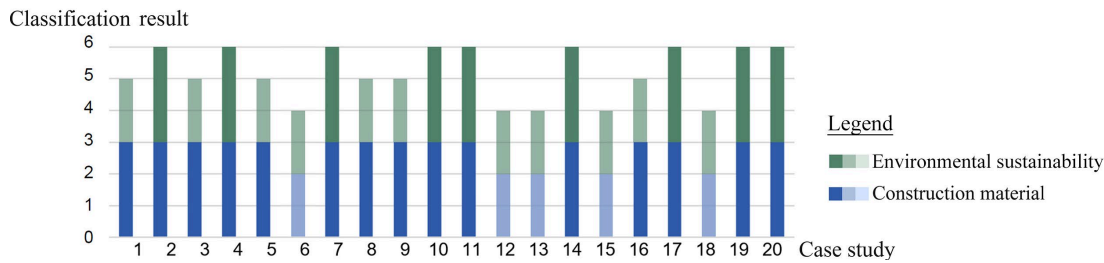


Figure 3: Stacked bar chart of construction materials and environmental sustainability across the analyzed case studies. Darker tones indicate lower embodied carbon in construction materials and better environmental performance.

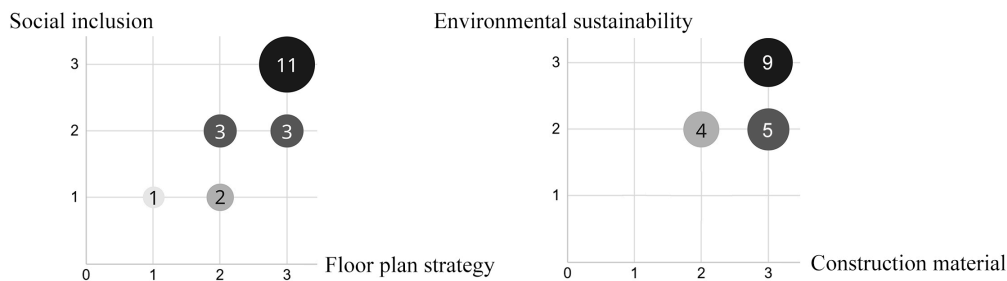


Figure 4: Bubble charts illustrating the relationship between floor plan strategies and social inclusion (left), and construction materials and sustainability (right) across the twenty analyzed case studies. Bubble size and color intensity indicate frequency, with the number of occurrences shown inside each bubble.

The results reveal a strong correlation between flexible floor plan strategies and social inclusion in the analyzed case studies. As shown in Figures 2 and 4 (left), most case studies are classified within the highest categories for both adaptability and inclusion. The predominant classification pairing, highly flexible floor plans and highly inclusive design approaches, occurs in 11 of 20 projects (55%), indicating that adaptable spatial configurations support diverse residential needs and inclusive living environments.

Figures 3 and 4 (right) demonstrate a similar correlation between construction materials and environmental sustainability. Most projects are classified within the highest categories for both criteria, suggesting that timber-dominant construction is frequently associated with stronger environmental performance. The most frequently occurring classification pairing, namely the highest classification for both construction material and ecological sustainability, occurs in 9 of 20 projects (45%). These projects integrate timber construction with resource-efficient material use, and passive house strategies.

Overall, the findings show that most case studies cluster within the highest classification categories, reflecting a prevailing tendency in contemporary densification projects in the DACH region to combine spatial adaptability, social inclusion, and environmental sustainability.

4. Vertical extension with timber

Timber-based construction is particularly suitable for vertical extensions, enabling sustainable densification without outward urban expansion. Compared to conventional mineral-based construction materials, timber is significantly lighter while still providing high structural capacity, making it ideal for interventions to existing buildings with limited load-bearing reserves. A timber-frame wall exhibits a substantially lower dead load, representing approximately 43% of that of a masonry wall and 31% of that of a reinforced concrete wall [3]. At the same time, structural load paths can be adapted to existing conditions, even across long spans, while the highly prefabricated construction enables rapid, precise, and weather-resilient assembly. Prefabrication also allows for fast, low-dust on-situ construction with minimal disruption, often enabling occupants to remain in the building throughout construction. Lastly, timber stores CO₂, contributing to climate change mitigation, while its strong thermal insulation properties make it ideal for energy-efficient refurbishment of existing building stock.

5. Vertical Extensions with the IntCDC multi-storey timber building system

However, despite the advantages of timber-based extensions, an analysis of 350 timber buildings constructed between 2000 and 2022 [6] found that most multi-storey timber systems rely on repetitive structural grids and modular layouts. These systems often incorporate steel or concrete hybridization (77.4%). They predominantly feature orthogonal geometries (76.3%), single-span slabs (98.9%), and grid-based support systems (98.2%), which limits their applicability in complex urban contexts.

To address these limitations, a point-supported flat slab system for multi-storey timber construction was developed at the University of Stuttgart through a co-design methodology [7][8][9]. The IntCDC multi-storey timber building system (MsTBS) integrates computational design, engineering, and robotic fabrication to increase material efficiency, structural performance, and geometric flexibility while enabling precise planning and prefabrication [10]. It uses up to 40% less material than conventional solid timber systems, reducing structural loads and foundation requirements for more cost- and material-efficient interventions. With spans of up to 11 m and cantilevers of up to 3 m, it can accommodate a variety of geometries and support conditions. The continuous, beamless slabs maximize usable space and allow for spatial flexibility and freedom.

6. Vertical extension construction systems

This section analyzes structural strategies for vertical densification at the top of existing buildings, focusing on load transfer between the existing structure and new timber-based stories. Six typical structural constellations were examined (Figure 5), defined by the interaction between roof extensions and the underlying structural system, alongside three additional strategies representing vertical extensions using the IntCDC MsTBS.

Variants (a–c) follow the existing structural logic by extending the original load-bearing system through: (a) the vertical continuation of load-bearing walls, (b) a skeleton frame aligned with the existing structural grid, and (c) parallel shear walls that continue the vertical load-bearing path. In contrast, variants (d–f) introduce a more independent structural system through: (d) external columns supporting the additional stories, (e) large-format wall elements arranged perpendicular to the existing supports, and (f) long-span beams spanning between exterior load-bearing walls and transferring loads perpendicular to the original structural layout, enabling more flexible column placement. Illustrations (g–i) demonstrate the adaptability and versatility of the IntCDC MsTBS across different structural conditions. In variant (g), existing columns continue upward to directly support the extension slab, accommodating both rectilinear and non-rectilinear grids with spans of up to approximately 11 m. Variant (h) extends existing columns or walls to support diverse structural configurations and cantilevers of up to 3 m. In variant (i), exterior load-bearing columns attached to the façade directly support the extension slab, creating a structurally independent system for the new addition.

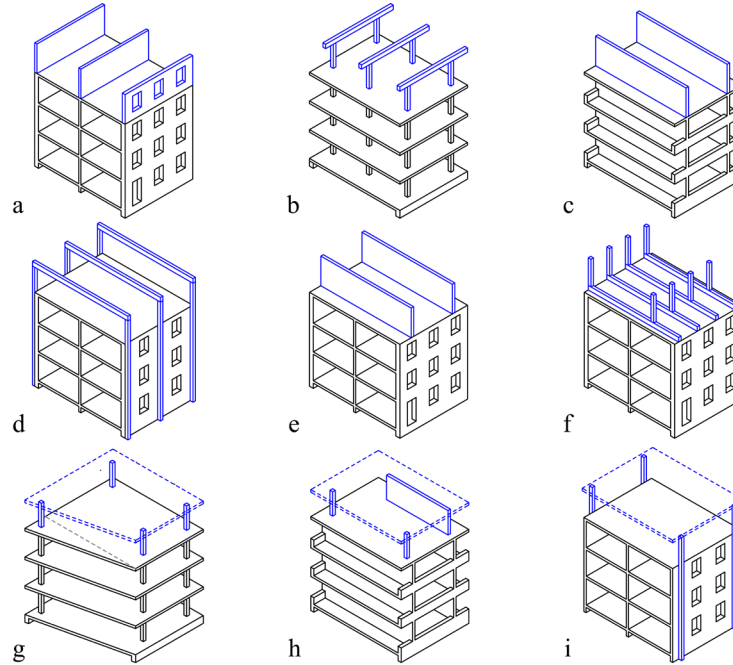


Figure 5: Structural configurations for timber-based vertical extensions. Illustrations (a–f) are adapted and slightly modified from [3], while (g–i) are based on the capabilities of the IntCDC MsTBS.

Collectively, the six initial variants illustrate a spectrum ranging from constructive continuity in (a–c) to structural decoupling in (d–f), demonstrating various ways of balancing heritage preservation, architectural legibility and load distribution in timber-based roof extensions. Variants (g–i) demonstrate the adaptability of the IntCDC MsTBS across various geometries, structural grids, and load-bearing conditions. The system enables long spans, flexible floor plans, and a wide range of support, setback, and cantilever configurations, all while ensuring lightweight construction and efficient load transfer. Finally, the beamless structural concept maximizes clear room heights and enhances spatial flexibility.

7. Case study Bebelallee

To explore new design paradigms for the vertical expansion of post-war housing estates, the Bebelallee project in Hamburg was selected as a case study (Figure 6). Designed originally by J. H. Burchard, the complex was constructed between 1955 and 1959, and then densified and modernized by Blauroam Architekten between 2008 and 2010. The cross-wing originally comprised three stories, while the adjacent buildings had two. The densification strategy added one or two stories, creating a uniform four-story configuration. As a result, the number of apartments increased from 104 to 151. The floor area ratio rose from 0.5 to 1.1, the site coverage from 0.2 to 0.3, and the density factor from 0.4 to 0.9 [11].

The existing units range from one- to three-room apartments (40–70 m²), while the extension introduced two- to three-room maisonette units (70–140 m²), targeting families and younger households. All units include balconies or roof terraces. The extensions were built using a hybrid mass timber frame structure, supported by columns in front of the existing façades and connected to reinforced concrete beams, while the foundations were also reinforced to support the additional loads [11].

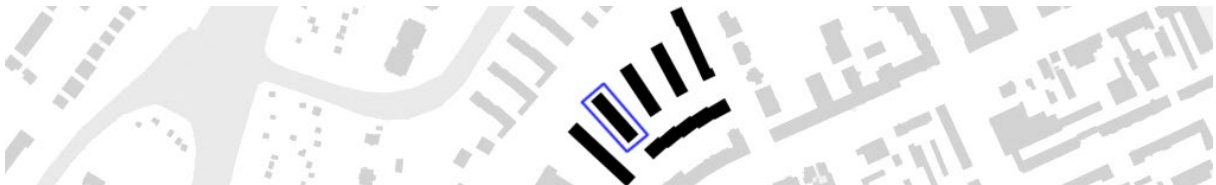


Figure 6: Site plan of Bebelallee. The building highlighted in blue corresponds to the floor plan drawings presented in Figure 7. The site plan is adapted from published images provided by Blauroam Architekten [11].

Architecturally, the additions feature a sculptural form with projections, recesses, and flat roofs. Cantilevers were avoided on south-facing façades to avoid shading, while north-facing façade project up to two meters. The zigzag articulation of the north façade mitigates direct overlooking by redirecting selected sightlines by 90° in response to reduced inter-building distances. As part of the energy-efficient renovation, the existing façades were insulated and re-clad with exposed gray brickwork, while ventilated cedar shingles emphasize timber as the dominant material of the extensions. These interventions define the estate's contemporary appearance. However, although the project improved housing capacity, apartment typologies, and environmental performance, accessibility remains limited due to raised ground floors and the absence of elevators [11].

7.1. New design paradigms for Bebelallee

The proposed intervention for the Bebelallee housing estate aims to address three key challenges commonly associated with the densification of post-war housing estates: improving environmental sustainability, enhancing accessibility, and incorporating non-rectilinear forms for vertical extensions. By integrating the IntCDC MsTBS, the project seeks to reduce environmental impact by avoiding the use of mineral-based materials and lowering structural weight through efficient timber use. At the same time, it aims to create more inclusive living conditions by improving accessibility. Furthermore, the IntCDC system's flexibility enables architectural forms that transcend conventional rectilinear extensions, contributing to a more diverse and contemporary building expression.

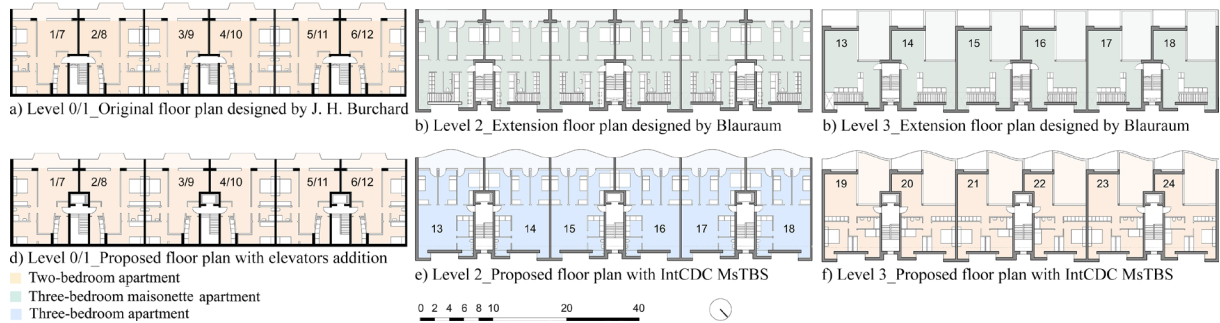


Figure 7: Existing floor plan configuration of the Bebelallee housing estate (top) and proposed floor plan configuration based on the IntCDC MsTBS (bottom). The existing floor plan drawings were adapted from published material [12].

Figure 7 illustrates the existing and proposed floor plan configurations for the Bebelallee housing estate. The original two-bedroom apartment layout is presented alongside the addition of three-bedroom maisonette units in the vertical extension on Levels 3 and 4. The redesigned plans introduce new apartment layouts, including three-room units on Level 3 and two-bedroom units on Level 4. These changes increase the number of apartments per building from 20 to 26 across the three identical volumes. The integration of elevators is central to the proposal, significantly improving accessibility. Additional measures, such as non-rectilinear balconies and terraces on the southeast façade, expand outdoor space and enhance architectural expression, improving spatial quality and supporting long-term usability.

Collectively, the proposed design demonstrates how timber construction can act as a catalyst for ecological transformation, social sustainability, and innovative approaches to adapting existing housing stock. The IntCDC MsTBS shows strong potential as an adaptive timber system for transforming post-war housing estates. It enables the addition of 32 additional residential units, diversifies dwelling types, improves accessibility, allows for greater design freedom, and enhances the overall quality of the residences.

8. Structural analysis

To verify the applicability of the IntCDC MsTBS for the vertical extension of the Bebelallee housing estate, structural simulations were conducted to determine the required slab thickness for both the Blauraum Architekten configuration and the proposed adapted floor plan (Figure 7). The analysis comprised a sequence of steps to pre-dimension slab thicknesses, with the aim of maximizing span lengths while maintaining reasonable slab thickness. First, column positions were defined under consideration of

the existing load-bearing wall elements to ensure a direct vertical load transfer into the foundations. Subsequently, the slabs were segmented into prefabricated elements as required by the building system [9]. Figure 8 (a, b) shows the segmentation performed using the square-merger method [13], as well as the resulting layouts analyzed using the FE SOFiSTiK software.

Since the self-weight of the slab structures was unknown at this stage, it was considered to be $g_{k,k} = 1.30 \text{ kN/m}^2$. Additionally, a superimposed expansion load of $g_{e,k} = 1.00 \text{ kN/m}^2$ and a live load of $q_k = 3.00 \text{ kN/m}^2$ were considered. The required minimum slab thickness was determined iteratively by performing structural checks for the ultimate limit state (ULS) and the serviceability limit state (SLS) for different cross-sectional build-ups of the timber hollow-slab system.

Since force concentrations occur around the columns, bending and rolling-shear verifications were performed at all column locations under ULS conditions. The ULS analyses were based on the fundamental load combination according to Eurocode 0 (Equation 1), while deflection checks for the SLS were carried out using the characteristic load combination according to Eurocode 0 (Equation 2).

$E_d = 1,35 \cdot g_k + 1,35 \cdot g_{e,k} + 1,50 \cdot q_k$	(1)
$E_d = 1,00 \cdot g_k + 1,00 \cdot g_{e,k} + 1,00 \cdot q_k$	(2)

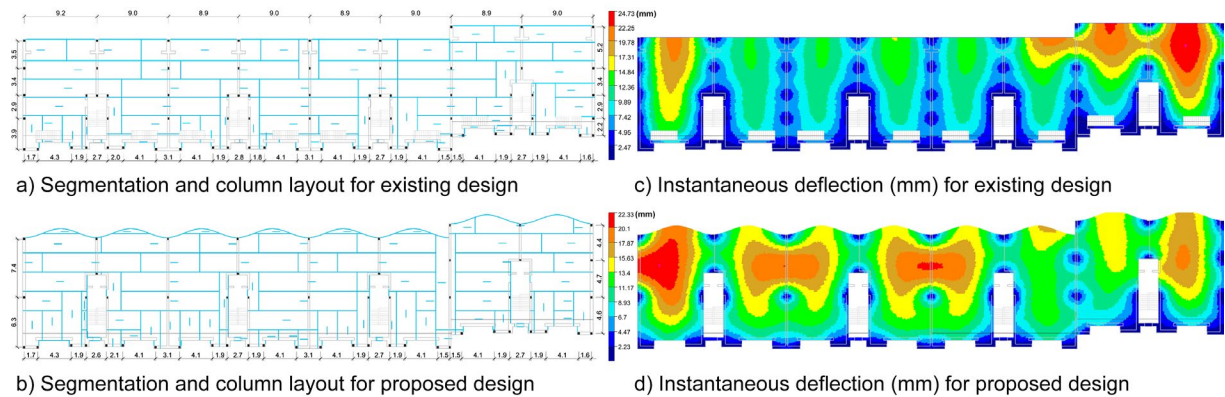


Figure 8: Segmentation, column layouts (left) and corresponding instantaneous deflections (mm) (right) for the existing (top) and proposed (bottom) floor plans under the characteristic load combination, based on the IntCDC MstBS.

Table 2 summarizes the resulting cross-sectional build-ups, average weight per square meter, and maximum span lengths. The utilization ratios obtained from the structural verifications are summarized in Table 3. As the results indicate, the SLS deflection checks govern the design and are therefore decisive in determining the minimum required slab thickness. The SLS assessment considered both instantaneous and final deflections, with higher utilization ratios obtained for instantaneous deflections. The corresponding deflection distributions are shown in Figure 8 (c, d).

Table 2: Cross sectional build-up, weight and max. span for both extension options.

	Min. required thickness	Layer Build-Up	Weight	Max. Span		
	[cm]	[mm]	[kg/m ²]	Length [m]	Width [m]	Area [m ²]
Existing floor plan configuration	34.0	Top panel: 100 (5 x 24) Hollow-Core: 100 Bottom panel: 100 (5 x 24)	111.72	9.00	5.20	46.80
Proposed floor plan configuration	40.0	Top panel: 100 (5 x 30) Hollow-Core: 100 Bottom panel: 100 (5 x 30)	136.92	9.20	6.00	55.20

Table 3: Utilizations in the ULS and SLS for both extension options.

	ULS			SLS			
	Max. Cross-sectional utilization			Deflection			
	Bending x-Direction	Bending y-Direction	Rolling Shear combined directions	Relevant Deflection [mm]	Span L [m]	Limit L/300 [mm]	Max. Utilization
Existing floor plan configuration	72 %	50 %	63 %	25	9.00	30	84%
Proposed floor plan configuration	66 %	62 %	68 %	23	7.50	25	92%

9. Environmental analysis

The environmental performance of the Bebelallee housing estate is evaluated based on sunlight exposure, a critical factor in passive house strategies. Adequate daylight reduces the need for artificial lighting, while solar gains contribute to passive heating and the efficient operation of photovoltaic systems, thereby improving the estate's overall energy efficiency. Thus, the analysis examines solar access and shading in current and proposed conditions. An incident radiation analysis was conducted for December 21 (winter solstice) to represent the most critical condition for daylight availability and solar access (Figure 9). The results show slight improvements between the original and the new design scenarios. The proposed configuration increases solar exposure on the southwest façade due to the larger surface area created by the curved slab geometry, while the northwest façade remains largely unchanged. The first two stories are unaffected by the additional stories and the 2 m cantilevers above them. Overall, the findings suggest that carefully designed vertical extensions can be implemented with minimal impact on a building's existing solar performance.

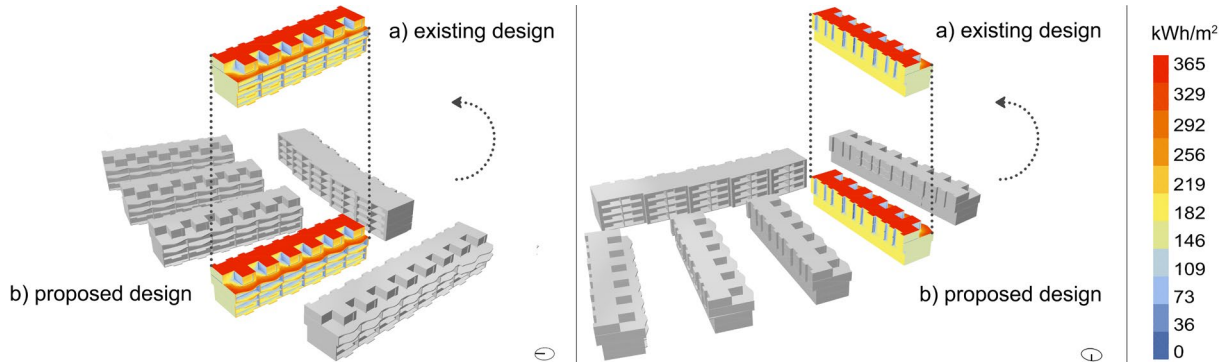


Figure 9: Incident radiation analysis (kWh/m²) for one of the buildings, comparing (a) the existing design (top) with (b) the proposed building extension configuration with the IntCDC MsTBS (bottom).

10. Results

The analysis reveals a clear trend in densification projects of post-war housing estates in the DACH region toward the spatial reconfiguration of existing floor plans, social inclusion, and environmental sustainability. More than half of the analyzed case studies (55%) combine extensive floor plan adaptations with highly social inclusive design strategies. Meanwhile, 45% combine timber construction with the highest environmental sustainability classification. Overall, 75% of the selected projects use timber construction systems, which highlights timber's suitability for densification due to its low weight, prefabrication capability, rapid construction, and low embodied carbon.

Structural simulations demonstrate the IntCDC MsTBS's high adaptability to varying structural conditions and building layouts. This enables large spans, irregular building geometries, flexible floor plans, lightweight construction, and efficient load transfer. However, the analysis indicates that these advanced capabilities are unnecessary for very simple slab geometries. Simple slab structures with rectilinear forms, short spans of approximately 5 meters, and a grid-based configuration of structural elements could be realized using conventional timber construction systems. Environmental simulations show that carefully designed vertical extensions have a minimal impact on the existing structure's solar access while improving the building's overall energy performance by increasing solar gain and replacing underperforming roofs.

11. Discussion and Conclusion

This study demonstrates how computational design, structural optimization, and environmental simulation can support the sustainable densification of post-war housing estates through timber-based extensions. The IntCDC MsTBS accommodates diverse structural and architectural requirements, enabling flexible floor plans, design freedom, and material- and energy-efficient construction. However, the findings also highlight the importance of selecting construction systems tailored to project-specific requirements.

Future research should expand the scope of the study to include a broader range of innovative design proposals for densifying post-war housing estates. Additionally, the suitability of the IntCDC MsTBS for other building typologies will be assessed, and an integrated computational design workflow will be developed that incorporates additional performance criteria and supports multidisciplinary participation and decision-making in the early design stages.

Acknowledgements

The project funding was provided by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/2 – 390831618.

Author Contributions

M.P.: Conceptualization, Methodology, Dataset generation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. L.R.: Visualization, Writing – structural analysis section. H.J.W., J.K., and A.M.: Supervision, Validation, Writing – review & editing.

References

- [1] S. Hofmeister Ed., *DETAIL 4.2020: Nachverdichtung / Increasing Density*. Munich: DETAIL Business Information GmbH, pp. 22-25, Apr. 2020.
- [2] K. U. Tichelmann, M. Günther et al., *Deutschlandstudie 2019: Wohnraumpotenziale in urbanen Lagen – Aufstockung und Umnutzung von Nichtwohngebäuden*. Technische Universität Darmstadt & Pestel Institut, 2019.
- [3] S. Krötsch, M. Stieglmeier and T. Engel, *Holzbau im Bestand*. DETAIL Praxis. Munich: DETAIL Business Information GmbH, 2024.
- [4] Statistisches Bundesamt (Destatis), *Wohnungen in Wohn- und Nichtwohngebäuden, Wohnfläche, Räume: Deutschland, Stichtag*. GENESIS-Online Datenbank, Tabelle 31231-0001, accessed May 28, 2026.
- [5] Vertical Extensions of Post-War Housing Estates: Comparative Analysis of Existing Projects in the DACH Region (view at <https://darus.uni-stuttgart.de/dataset.xhtml?persistentId=doi:10.18419/DARUS-6145>)
- [6] H. Svatoš-Ražnjević, L. Orozco and A. Menges, “Advanced timber construction industry: A review of 350 multi-storey timber projects from 2000–2021,” *Buildings*, vol. 12, no. 4, p. 404, 2022.
- [7] A. Krtschil, L. Orozco, S. Bechert, H. J. Wagner, F. Amtsberg, T.-Y. Chen, A. Shah, A. Menges and J. Knippers, “Structural development of a novel punctually supported timber building system for multi-storey construction,” *Journal of Building Engineering*, vol. 58, p. 104972, 2022.
- [8] L. Orozco, A. Krtschil, H. J. Wagner, S. Bechert, F. Amtsberg, J. Knippers and A. Menges, “Co-design methods for non-standard multi-storey timber buildings,” *Sustainability*, vol. 15, no. 23, p. 16178, 2023.
- [9] S. Tremml, L. Riedel, H. J. Wagner, J. Knippers and A. Menges, “Concept to Construction: Co-Design and Integrative Development Processes for the IntCDC Multi-Story Timber Building System,” in *WCTE 2025*
- [10] M. Papadimitraki, H. J. Wagner and A. Menges, “Digital Participation in Sustainable Urban Densification: Exploratory Design Methods for Timber Building Stock Extensions,” in *Proceedings of CAADRIA 2026*
- [11] L. Kaufmann, “Nachverdichtung im Städtebau: Transformative Strategien für Zeilenbausiedlungen der Nachkriegsmoderne,” *Architekturen*, vol. 86, Bielefeld: transcript Verlag, 2024.
- [12] <https://blrm.eu/auswahl/0652-treehouses-bebelallee>, accessed May 28, 2026.
- [13] L. Orozco, H. J. Wagner, A. Krtschil, J. Knippers and A. Menges, “Computational Segmentation of Timber Slabs with Free Column Placement,” *Computer-Aided Design*, vol. 168, p. 103650, 2024