

Digital reconstruction: 3d-printed modular housing and urban renewal strategies in post-war Kharkiv

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Abstract. The large-scale destruction of residential areas in Kharkiv during the Russian invasion of Ukraine has exposed the limitations of conventional post-war reconstruction approaches based on full demolition and standardized replacement. Soviet panel housing estates, which constitute the dominant residential typology in the city, require recovery strategies that combine rapid implementation with long-term spatial, social, and architectural adaptability. While recent international initiatives and academic studies have identified Kharkiv as a key testing ground for post-conflict urban recovery, the majority of the existing research focuses on modular prefabrication and logistical frameworks, leaving the architectural potential of digital fabrication technologies insufficiently explored.

The aim of this paper is to develop and evaluate a digital reconstruction strategy based on the integration of 3D-printed modular housing units into partially damaged panel buildings. The proposed approach introduces an architectural “patch” that selectively replaces destroyed fragments while preserving existing structural frameworks. The scientific novelty of the study lies in applying additive manufacturing not only as a construction method but as a design-driven tool for selective architectural intervention and urban renewal. The practical value of the research is demonstrated through a scalable reconstruction model that enables rapid deployment, material efficiency, and architectural diversification of monotonous housing estates. The results indicate that 3D-printed modular interventions can enhance both the housing quality and urban identity, offering a transferable solution for post-war reconstruction in Kharkiv and other cities with similar housing stock.

1. Introduction

Armed conflicts of the early twenty-first century continue to expose the vulnerability of large-scale residential environments and reveal the long-term urban consequences of warfare [1-3]. Beyond immediate humanitarian losses, the destruction of housing stock produces enduring architectural, social, and economic challenges that influence post-war urban development over extended periods [4]. In cities largely shaped by mass housing estates constructed during the second half of the twentieth century, post-war reconstruction confronts a fundamental dilemma: whether to pursue large-scale demolition or to adopt adaptive strategies that retain existing urban



structures while meeting contemporary requirements of safety, sustainability, and habitability [5-7].

Kharkiv, one of Ukraine's major industrial and educational centers, exemplifies these challenges. Since the onset of the full-scale invasion, multiple residential districts of the city have been subjected to sustained and recurrent damage. Although destruction has affected various parts of the urban fabric, the Northern Saltivka housing estate has experienced the most extensive and systematic impacts. This condition positions Northern Saltivka as a representative case for examining post-war reconstruction strategies in large-scale panel housing developments [8,9].

Post-war housing reconstruction has been widely addressed in recent architectural and urban research across diverse geopolitical contexts. A substantial body of literature indicates that large-scale demolition frequently results in social displacement, prolonged recovery processes, and the gradual loss of local urban identity [1,10]. Conversely, studies focused on the regeneration of mass housing estates emphasize the capacity of selective refurbishment, structural adaptation, and incremental renewal to strengthen urban resilience and support social sustainability [11-13]. Nevertheless, much of this research concentrates on long-term physical deterioration or socioeconomic obsolescence, offering limited insight into reconstruction following sudden, war-induced structural damage.

In parallel, recent studies increasingly investigate modular construction systems and digital fabrication technologies as instruments for accelerating housing provision and improving construction efficiency. Additive manufacturing, particularly three-dimensional concrete printing, has attracted attention due to its potential to reduce material consumption, shorten construction timelines, and allow for architectural customization [14-16]. However, existing research predominantly addresses digital construction, digital fabrication, and digital twin technologies within the context of new-build projects and general lifecycle management of the built environment. While these approaches are increasingly applied to design, construction, and operation phases, their application in the selective reconstruction of damaged residential buildings within established urban environments remains insufficiently explored [17].

Recent design-oriented studies have begun to explore adaptive and modular reconstruction strategies for war-damaged residential environments, emphasizing hybrid off-site and on-site systems, incremental growth, and the reuse of remaining structural frameworks. Case-based research focusing on Kharkiv highlights the potential of modular architectural interventions to support rapid reoccupation while enabling long-term spatial and social adaptability. However, these approaches primarily address prefabrication and modularity and do not yet integrate digital fabrication or additive manufacturing technologies as active instruments of selective post-war reconstruction [18].

This paper examines a digital post-war reconstruction strategy for residential districts based on the selective integration of three-dimensionally printed modular housing units into partially damaged large-panel buildings. The scientific novelty of the study lies in reframing additive manufacturing from a technology primarily associated with new construction into an architectural and urban design instrument for adaptive post-war renewal. By focusing on Northern Saltivka as a case study, the research contributes to ongoing discussions on resilient reconstruction strategies for cities affected by prolonged armed conflicts.

2. Research methodology

This study adopts a design-based research methodology to examine strategies for post-war reconstruction of large-scale residential housing. The methodological framework combines case

study analysis, qualitative assessment of damage conditions, and architectural design exploration in order to evaluate selective reconstruction as an alternative to large-scale demolition. Particular attention is given to scenarios in which partially damaged buildings retain structural capacity and can be adapted through the integration of modular housing units produced using digital fabrication technologies.



Figure 1. Location of the Northern Saltivka housing estate within the urban structure of Kharkiv. The figure serves solely as a locational reference and does not represent the overall extent or distribution of destruction across the city.

The methodology is structured around the analysis of a representative urban case, followed by the identification of damage patterns, design-based testing of reconstruction scenarios, and evaluation of modular integration strategies under real spatial and structural constraints. This approach allows architectural design to function not only as a representational outcome, but also as an analytical instrument for assessing post-war reconstruction potential.

2.1 Case study selection and spatial context

The research is based on the case study of the Northern Saltivka housing estate in Kharkiv. The selection of this area is determined by the scale, persistence, and heterogeneity of war-related damage affecting its residential fabric. Since the beginning of the full-scale invasion, destruction has occurred repeatedly and unevenly across the city, resulting in a wide range of damage conditions within similar building typologies.

Northern Saltivka is predominantly composed of multi-storey prefabricated large-panel residential buildings constructed in the late twentieth century. These buildings are characterized by standardized structural systems, repetitive layouts, and high residential density, making the district representative of mass housing developments common in many post-socialist cities.

The design proposals analyzed in this study are based on an architectural project developed by K. Rusiev and A. Podolianykh [19] and are used here as a research case for methodological analysis rather than as an original design contribution. The project is examined as an applied

architectural framework that enables the evaluation of selective reconstruction strategies under post-war conditions.

2.2 Damage assessment and reconstruction scope

In the context of large-scale armed conflicts, not all damaged residential buildings are suitable for

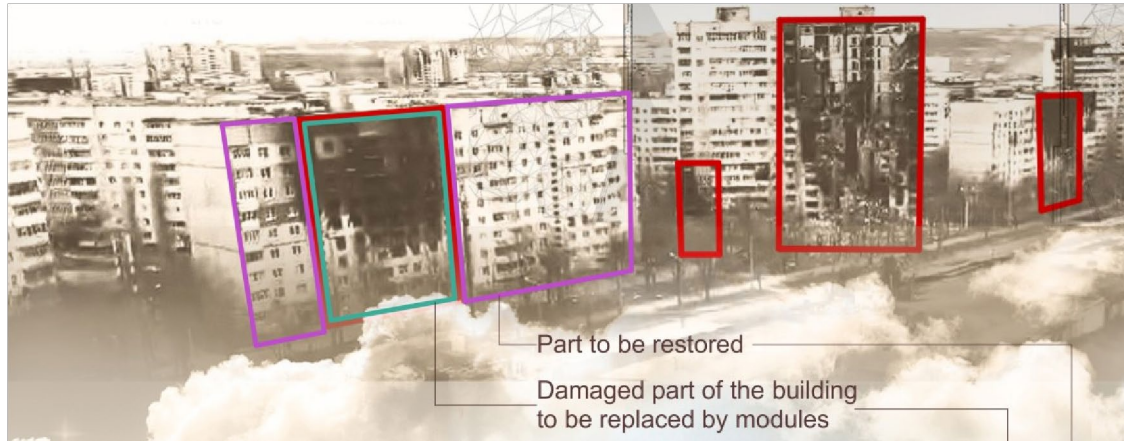


Figure 2. Identification of partially damaged building fragments and areas designated for selective replacement by modular units in the Northern Saltivka housing estate (Kharkiv).

reconstruction. In many cases, complete demolition represents a more rational solution due to safety concerns, structural instability, or economic constraints.

Accordingly, the present study deliberately limits its scope to buildings that retain partially intact load-bearing systems and demonstrate potential for selective architectural intervention.

Damage assessment is based on the interpretation of open satellite imagery, photographic documentation, and publicly available reports. Within Northern Saltivka, a significant proportion of buildings exhibit partial damage rather than total structural collapse. Typical conditions include the loss of façade segments, destruction of corner sections, damage to individual apartments, and localized damage of floor slabs. In such cases, the structural core of the building often remains stable, allowing for reconstruction strategies that avoid full replacement.

The distinction between buildings requiring demolition and those suitable for selective reconstruction forms a key methodological premise of the study. The conceptual logic of selective removal and modular replacement is illustrated in Figure 2.

2.3 Design-based analytical approach

Architectural design is employed in this research as an analytical tool rather than as a purely representational outcome. A design-based research approach enables the testing of reconstruction scenarios under real spatial, structural, and urban constraints. Through iterative digital modeling, alternative strategies are developed and evaluated in terms of spatial coherence, adaptability, and architectural feasibility.

This project-based analysis makes it possible to move beyond abstract typological reasoning and assess reconstruction strategies through concrete spatial configurations. Particular attention is paid to the compatibility of new residential elements with the existing panel construction systems and to the continuity of the surrounding urban fabric.

Figure 3 illustrates the modular logic of the proposed reconstruction approach through the integration of new housing units into a partially damaged large-panel building.

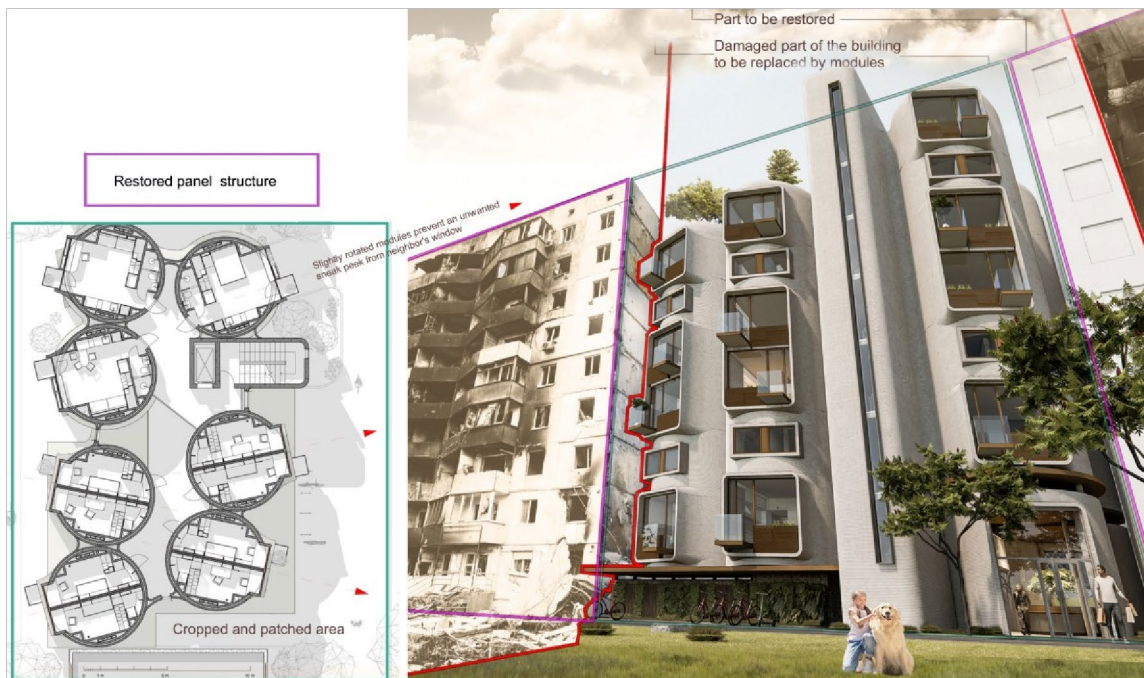


Figure 3. Modular reconstruction logic illustrating the integration of three-dimensionally printed housing units into a partially damaged large-panel residential building (architectural project by K. Rusiev and A. Podolianykh).

2.4 Modular integration strategy and digital fabrication

Based on the identified damage patterns and spatial constraints, a strategy of selective modular integration is proposed. Instead of demolishing entire buildings, damaged fragments are locally dismantled and replaced with newly designed residential modules. This strategy prioritizes minimal intervention, structural compatibility with existing panel systems, and the preservation of functional building components wherever possible.

Digital fabrication, specifically three-dimensional concrete printing, is considered as an enabling technology within this framework. In this study, additive manufacturing is understood as a layer-by-layer construction process that allows the production of architecturally differentiated components without conventional formwork. Digital fabrication is treated not as a tool exclusively associated with new construction, but as part of a broader architectural strategy for adaptive post-war renewal of partially preserved residential buildings.

The study is intentionally framed as a design-based architectural investigation; detailed structural calculations, regulatory compliance procedures, and economic feasibility assessments are considered subsequent stages of interdisciplinary research.

3. Results and discussion

The proposed digital reconstruction strategy demonstrates that the selective integration of three-dimensionally printed modular housing units into partially damaged large-panel residential buildings can generate coherent architectural, functional, and urban outcomes without resorting to major demolition. The results are discussed across spatial, functional, and urban scales to evaluate the broader implications of the approach for post-war residential reconstruction.

3.1 Spatial and structural outcomes of modular integration

The integration of modular units into existing residential structures enables the reconfiguration of damaged building fragments while preserving the primary load-bearing framework of the original large-panel system. As illustrated in Figure 3, modular elements are positioned to replace structurally compromised sections, while intact structural components remain operational. This approach maintains vertical and horizontal continuity within the building volume and avoids abrupt structural or spatial discontinuities between preserved and reconstructed parts.

While the proposed modular integration preserves the primary load-bearing framework of the existing panel system, the study does not aim to replace engineering verification. Structural calculations and experimental testing of the integrated modules are required prior to implementation and represent a necessary next phase of research.

From an architectural perspective, the insertion of modular volumes transforms the façade articulation and overall volumetric expression of the building. The differentiated geometry of the modular additions contrasts with the repetitive logic of the original panel housing, creating a legible distinction between retained and reconstructed elements. Rather than masking war-related damage, this contrast frames reconstruction as a visible process of transformation. At the same time, the modular system respects the existing building height, alignment, and urban scale, ensuring compatibility with the surrounding residential fabric.

3.2 Technological implications of additive manufacturing

The technological foundation of the proposed reconstruction strategy relies on additive manufacturing, specifically three-dimensional concrete printing, as illustrated in Figure 4. The use of on-site digital fabrication enables the production of modular housing units with reduced material waste, shortened construction timelines, and limited dependence on conventional labor-intensive construction processes. These characteristics are particularly relevant in post-war contexts, where resource constraints, disrupted supply chains, and labor shortages often complicate large-scale rebuilding efforts.

Beyond efficiency considerations, additive manufacturing provides a high degree of formal flexibility, allowing the generation of non-standard geometries that respond to irregular damage patterns and existing structural constraints. This flexibility supports adaptive architectural solutions that would be difficult to achieve using traditional prefabrication methods. In this sense, digital fabrication operates not only as a construction technology but also as a design instrument.

3.3 Functional adaptability and modular aggregation

At the level of residential organization, the proposed reconstruction approach is underpinned by a repeatable cylindrical housing unit, referred to as “Module A”. The aggregation logic of this unit is shown in Figure 5, demonstrating how vertical stacking, mirroring, and clustering can generate diverse residential configurations while maintaining a coherent structural system. This modular logic allows damaged building sections to be reconstructed incrementally, adapting the number and arrangement of units to specific site conditions and degrees of destruction.

The internal organization of the modules supports functional flexibility and accommodates different household structures and living scenarios. Unlike temporary post-disaster housing solutions, the proposed modules are conceived as permanent residential units integrated into the existing housing stock. Their spatial configuration meets long-term habitation standards, including adequate daylight access, private outdoor spaces, and the potential for internal reconfiguration. As a result, the modular intervention contributes not only to quantitative housing replacement but also to qualitative improvements in living conditions.

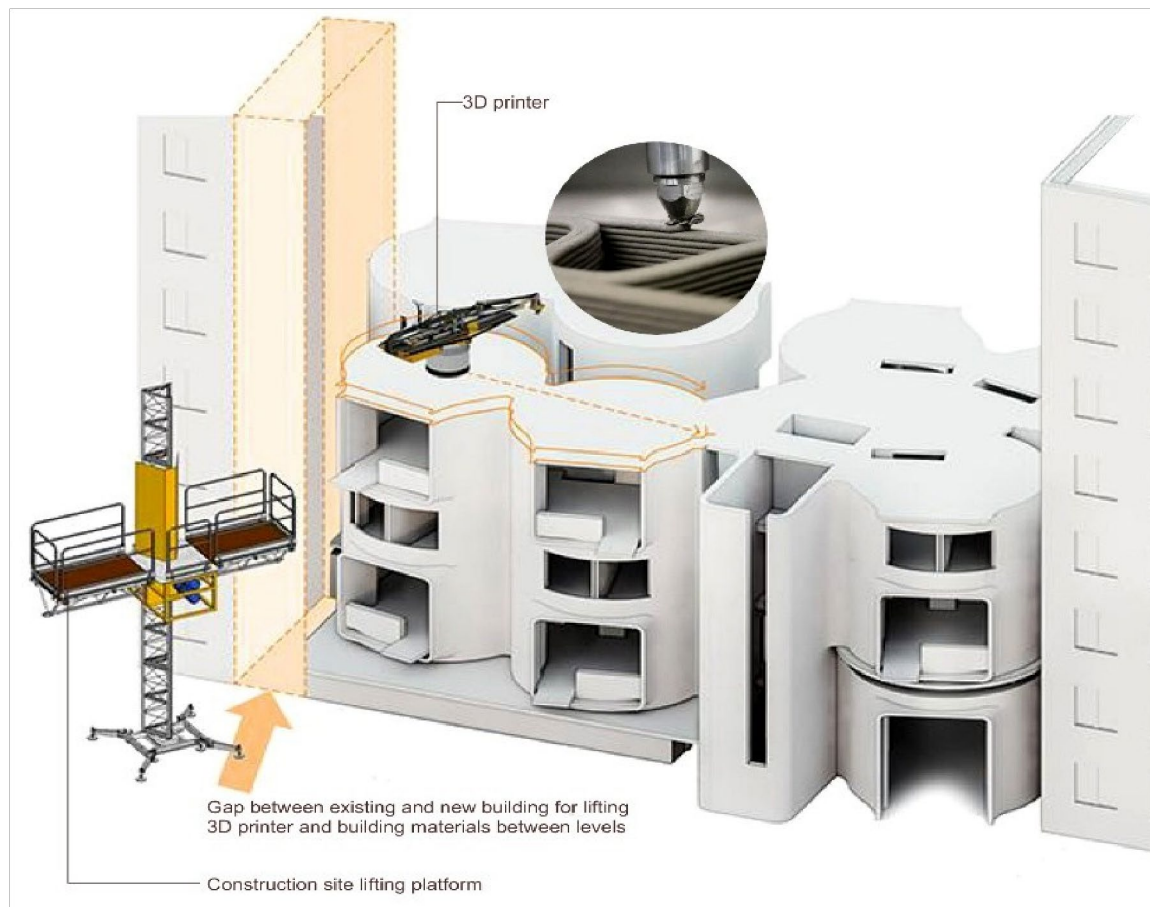


Figure 4. Conceptual diagram of on-site three-dimensional concrete printing applied to the selective reconstruction of a partially damaged large-panel residential building, illustrating the integration of printed modules and construction logistics (architectural project by K. Rusiev and A. Podolianykh)

3.4 Urban and social implications

At the urban scale, the selective reconstruction strategy offers a viable alternative to large-scale demolition, which is frequently associated with social displacement, loss of local identity, and extended redevelopment timelines. By retaining substantial portions of the existing residential structure, the proposed approach supports continuity of place and preserves elements of collective memory within the housing estate.

The incremental nature of modular integration enables phased reconstruction aligned with financial, technical, and organizational constraints typical of post-war recovery processes. This phased implementation reduces the need for full resident relocation and allows for gradual reoccupation of restored buildings. Consequently, the strategy contributes to urban resilience by combining architectural adaptability with social sustainability, positioning digital modular reconstruction as a viable tool for the long-term recovery of war-affected residential districts.

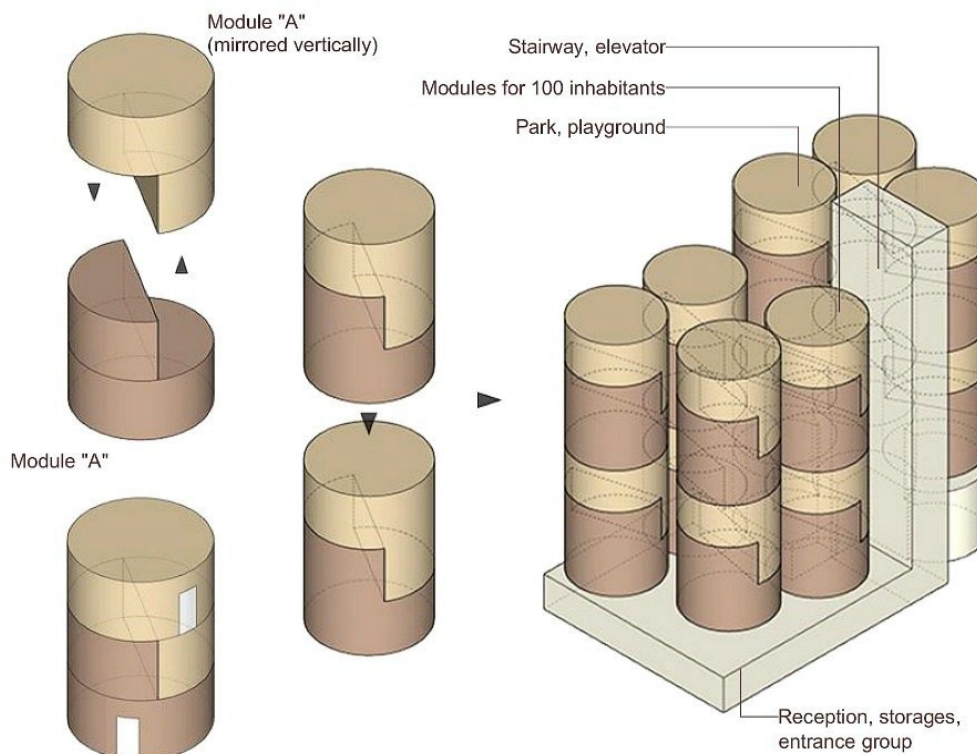


Figure 5. Modular aggregation scheme of three-dimensionally printed housing units, showing the base module (Module “A”), its mirrored variants, and the formation of a residential cluster (architectural project by K. Rusiev and A. Podolianykh).

From an economic perspective, selective modular reconstruction offers a potential alternative to full demolition and conventional capital renovation. By limiting demolition volumes, enabling phased implementation, and reducing relocation needs, the approach may lower indirect social and infrastructural costs. A detailed cost comparison, however, requires life-cycle assessment and market-based data and is beyond the scope of the present study.

4. Conclusion

This study explored the potential of digitally fabricated modular housing as an adaptive strategy for the post-war reconstruction of large-panel residential buildings, using the Northern Saltivka housing estate in Kharkiv as a representative case. The research focused on buildings that have sustained partial structural damage and therefore retain the potential for selective reconstruction rather than complete demolition.

The proposed approach demonstrates that three-dimensionally printed modular units can be integrated into existing panel structures while preserving the overall urban framework and minimizing displacement. The analysis shows that modular replacement of damaged building fragments allows for flexible architectural adaptation, improves spatial quality, and supports incremental reconstruction processes aligned with post-war resource constraints. In contrast to

conventional demolition-based strategies, this method enables targeted intervention and phased implementation within an occupied or gradually repopulated urban environment.

The research contributes to contemporary discussions on post-war urban resilience by repositioning additive manufacturing technologies as tools not only for new construction but also for adaptive renewal of existing housing stock. The findings indicate that digital fabrication offers advantages in terms of construction speed, form adaptability, and reduced dependency on extensive labor and logistics chains, which are critical factors in post-conflict contexts.

At the same time, the study is limited by its focus on a single architectural case and does not include structural testing, detailed engineering calculations, large-scale economic feasibility assessment, or regulatory approval procedures. These aspects are essential for real-world implementation and should be addressed through interdisciplinary collaboration in subsequent stages of research.

Future investigations should therefore integrate architectural experimentation with engineering validation, life-cycle assessment, and comparative analysis across different urban and geopolitical contexts. Nevertheless, the presented methodology constitutes a transferable framework for selective post-war reconstruction and may inform future strategies for the regeneration of mass housing estates affected by armed conflict.

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