

Article

Selected Modernization Problems of Large-Panel Buildings in the Context of the EU EPBD Directive

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Abstract

The article presents selected problems related to the modernization of large-panel buildings in the context of the requirements arising from the EU EPBD (Energy Performance of Buildings Directive). The study has an exploratory character and is based on qualitative case study analyses of selected large-panel residential buildings representing different prefabrication systems and modernization conditions. The characteristic features of prefabricated buildings are outlined, and the main modernization barriers are identified, including structural limitations, insufficient thermal performance of building envelopes, outdated technical systems, and organizational and legal challenges resulting from ownership structures. Particular attention is given to the EPBD requirements concerning energy efficiency improvement, CO₂ emission reduction, and the implementation of the zero-emission building (ZEB) standard. The analysis indicates that the modernization of large-panel buildings requires a systemic approach integrating technical, economic, and organizational measures. The importance of comprehensive thermal retrofitting and the integration of renewable energy sources is emphasized. The findings also suggest that digital tools such as BIM (Building Information Modeling) may support modernization planning and building information management. The conclusions of the article indicate that the effective implementation of the EPBD provisions for large-panel buildings will only be possible with simultaneous systemic support, including financial and regulatory instruments, as well as the development of technical and organizational competencies within the construction sector.

Keywords: modernization barriers; deep renovation; large-panel buildings; EPBD directive; SWOT analysis



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1. Introduction

Residential buildings constructed using large-panel prefabricated technology constitute a significant component of the urban structure in many Central and Eastern European countries. However, despite common historical and technological backgrounds, these building stocks are not homogeneous, and their characteristics, technical condition, and the scope of previous modernization measures vary considerably between countries. In this paper, the detailed analysis was limited to the Polish national building stock, which, due to its scale, technological diversity, and availability of data, represents a representative case study for the broader regional context. It is estimated that these buildings, erected mainly during the second half of the twentieth century, still provide housing for a substantial part

of the population, making them a key area for modernization activities in the context of current energy and environmental challenges.

Considering the increasingly stringent climate policy of the European Union, the adaptation of the existing building stock to the requirements specified in the Energy Performance of Buildings Directive (EPBD) [1] has become particularly important. This directive defines the transformation pathway for the building sector, assuming a gradual achievement of high energy performance, reduction of greenhouse gas emissions, improvement of occupants' quality of life, and, ultimately, the transition towards zero-emission buildings. In practice, this requires deep renovation of existing buildings, including large-panel prefabricated residential buildings, which constitute a particular challenge due to their technological characteristics. Previous modernization measures applied to this building typology have primarily focused on improving the thermal insulation of external envelopes and partially upgrading building service systems. However, in light of current regulatory requirements and increasing user expectations, such an approach is no longer sufficient. Consequently, the implementation of comprehensive modernization strategies has become necessary.

The literature emphasizes the need for a multi-criteria approach in the modernization of existing buildings, considering not only technical aspects but also economic, environmental, and organizational factors [2]. Prefabricated buildings, which are widespread in Central and Eastern European countries, remain a particular challenge because their energy performance characteristics and structural limitations significantly affect the scope and effectiveness of possible renovation measures [3]. In this context, a systemic approach integrating different decision-making areas and enabling comprehensive renovation planning is becoming increasingly important. Based on the analysis of implemented and planned modernization measures in selected case-study buildings, supplemented by a literature review, both barriers and limitations, as well as opportunities for improving the energy performance of the large-panel building stock, were identified.

Although the technical characteristics and typical defects of large-panel buildings have been widely discussed in the literature, relatively few studies have analyzed these issues in the context of the requirements introduced by the revised EPBD directive. In particular, there is a lack of studies examining the extent to which technical, organizational, and ownership-related constraints may affect the implementation of deep renovation measures and the achievement of EPBD objectives in existing large-panel residential buildings. Therefore, this study adopts an exploratory qualitative approach based on selected case studies representing different large-panel prefabrication systems and modernization conditions. The purpose of the analysis is not to provide statistically representative results but to identify recurring modernization barriers and limitations that may affect the implementation of EPBD requirements in the existing large-panel building stock.

The aim of this paper is to identify and analyse selected modernization problems of large-panel residential buildings in the context of EPBD requirements. The study presents the characteristic features of large-panel technology, identifies the main renovation barriers, and indicates potential directions for actions enabling their effective adaptation to contemporary energy and environmental standards.

2. EPBD Requirements for Existing Buildings

The Energy Performance of Buildings Directive (EPBD) constitutes one of the key instruments of the European Union's climate and energy policy aimed at the decarbonization of the building sector. Buildings account for a significant share of final energy consumption and greenhouse gas emissions, which justifies the need to intensify modernization activities, particularly regarding the existing building stock. In the updated version of the directive, particular emphasis has been placed on achieving climate neutrality of the

building sector by 2050, while simultaneously reducing greenhouse gas emissions by at least 55% by 2030 [1]. These objectives are to be achieved through improving the energy performance of buildings, the gradual phase-out of fossil fuels in heating systems, and increasing the share of renewable energy sources.

One of the fundamental elements of the directive is the introduction of the Zero-Emission Building (ZEB) standard, which is intended to become the mandatory standard for new buildings in the coming years and subsequently for existing buildings undergoing progressive modernization. A zero-emission building is defined as a building with very high energy performance, in which energy demand is minimized and the remaining energy needs are covered, to the greatest possible extent, by renewable energy sources, while greenhouse gas emissions are reduced to nearly zero levels. In relation to existing buildings, this implies the need to implement so-called deep renovation measures, including not only improvements to the thermal insulation of building envelopes but also comprehensive modernization of technical systems and the integration of renewable energy sources.

The EPBD also introduces a new approach to the renovation of the existing building stock, based on the identification and gradual elimination of buildings with the lowest energy performance. Member States are required to develop national renovation plans defining pathways for reducing energy consumption in the building sector, as well as support mechanisms for renovation investments. Emphasis has been placed on increasing the scale and pace of deep renovation, leading to a significant improvement in building energy performance, in contrast to the previously dominant partial modernization measures. In practice, this means a transition from fragmented renovation activities towards a comprehensive approach that considers the entire building life cycle. To synthetically present the most important requirements of the directive and their implications for existing buildings, a summary is provided in Figure 1.

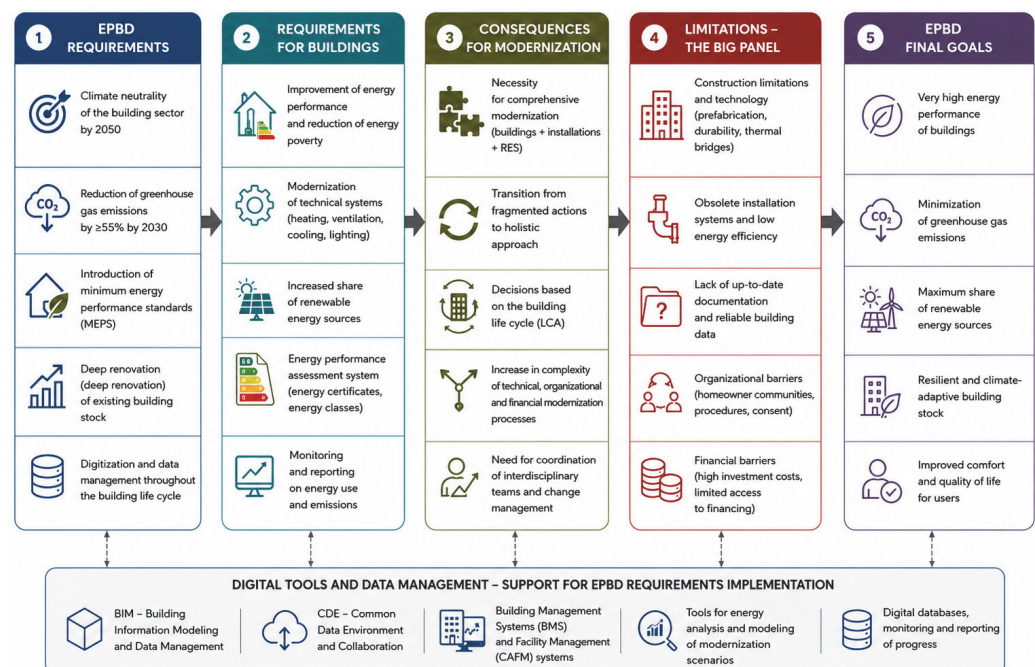


Figure 1. Diagram illustrating the relationships between the requirements of the Energy Performance of Buildings Directive and their implications for the modernization process of existing buildings, with particular emphasis on the limitations of large-panel building stock.

As shown in the summary presented in Figure 1, the requirements of the directive necessitate a transition from isolated interventions to comprehensive building modernization, covering both building envelopes and technical systems, as well as energy sources.

An important element of the directive is the development of building energy performance assessment systems. A key role is played by Energy Performance Certificates (EPCs), which should present the energy class of a building in a transparent and comparable manner. This assessment is based, among others, on indicators such as annual primary and final energy demand, CO₂ emission levels, and the share of renewable energy sources. The new regulations assume increased accessibility and transparency of these data, which is expected to support investment decision-making processes and improve the energy awareness of building users.

The directive also highlights the growing importance of digitalization and data management in improving building energy performance. It emphasizes the need to create and maintain reliable building databases. The integration and use of such information in decision-making processes may significantly support the planning and implementation of renovation measures. Although the directive does not specify technological tools, it clearly underlines the importance of a data-driven approach enabling the monitoring of progress towards climate objectives and the effective management of the building stock. In practice, this approach is implemented using tools such as Building Information Modeling (BIM), Common Data Environment (CDE) platforms, and Computer-Aided Facility Management (CAFM) systems, which enable the integration, updating, and analysis of building-related data throughout the entire building life cycle.

3. Characteristics of Large-Panel Buildings in the Context of Their Modernization

In Poland, large-panel construction still constitutes one of the most important segments of the existing multi-family residential building stock. According to data provided by the Building Research Institute (ITB), approximately 60,000 buildings constructed using this technology are currently in operation in Poland, comprising around 2.5 million apartments. The highest concentration of this type of development is in the Mazowieckie, Łódzkie, Śląskie, and Dolnośląskie voivodeships. The development of large-panel construction in Poland took place mainly between 1960 and 1990, with the peak of production and implementation occurring during the second half of the 1970s and the beginning of the 1980s. During this period, both nationwide and regional prefabrication systems were developed. The systems most frequently discussed in the literature include OWT-67, WUF-T, the Szczecin system, and later “open” systems such as W-70 and Wk-70. Against the background of the entire national housing stock, the scale of large-panel construction remains considerable even today. According to data from Statistics Poland (GUS), at the end of 2024 there were 15.97 million dwellings in Poland, including 10.84 million located in urban areas [4]. When compared with ITB estimates indicating approximately 2.5 million apartments constructed using large-panel technology, this represents around 15.7% of the total national housing stock and approximately 23.1% of the urban housing stock. This scale clearly demonstrates that large-panel buildings constitute an important component of the national strategy for improving the energy performance of the existing building stock.

In the context of modernization, it should be emphasized that these buildings are not homogeneous about prefabrication systems, structural solutions, construction quality, or subsequent operational modifications [5]. Polish literature and recent technical studies indicate that the main problems concern joints exposed to weather conditions, the condition of façade layers, thermal bridges, acoustic performance—particularly in inter-apartment walls [6]—hygienic and health-related issues [7], deterioration of building service systems, the effects of earlier “shallow” thermal retrofits, and functional limitations of apartments designed according to historical housing standards [8–11]. Additional attention is drawn to the functional constraints of apartments resulting from the adopted structural layouts

and design schemes. At the same time, diagnostic studies conducted in Poland on large samples of buildings demonstrate that, provided appropriate diagnostics, repairs, and modernization measures are carried out, there are no grounds for considering the entire large-panel building stock as unsafe for continued use. This constitutes an important argument supporting the continued operation and modernization of these buildings [6,12].

4. Selected Renovation Problems Based on Case Studies

4.1. Analyzed Buildings

The research methodology was based on a qualitative case study analysis aimed at identifying the key modernization problems of large-panel buildings in the context of the requirements of the EPBD directive. The scope of the conducted analyses included:

- analysis of the technical documentation of the buildings,
- architectural and construction inventory surveys,
- assessment of the technical and functional condition of the buildings,
- analysis of the scope and effectiveness of previous modernization measures,
- identification of problems in relation to current technical requirements and the assumptions of the EPBD directive.

The analysis was supplemented by on-site inspections, enabling verification of the actual condition of the buildings and identification of operational problems, such as deterioration of finishing elements, inadequacy of functional solutions, or non-compliance with current technical and construction regulations. The selection of buildings was purposive and focused on identifying the most common modernization problems occurring in large-panel buildings. The analyzed cases do not constitute a statistically representative sample; however, they allow for the identification of recurring phenomena and systemic limitations affecting a significant part of this building stock in Poland. The analyzed buildings were deliberately selected to represent different prefabrication systems, building scales, ownership structures, and locations. The objective was not to achieve statistical representativeness but to identify recurring modernization problems occurring under different technical and organizational conditions.

The subject of the analysis included residential buildings erected using large-panel technology in the second half of the twentieth century, representing different prefabrication systems and varying scopes of previous modernization measures (Table 1). Among the analyzed cases was a multi-family residential building located in Rzeszów, constructed using the RKL P-73 system. The building, completed in 1979, consists of five above-ground storeys and a single staircase core and is representative of small-scale large-panel residential development. Its structure is based on prefabricated load-bearing walls and floor slabs, with a characteristic transverse load-bearing wall arrangement and prefabricated vertical circulation elements.

Another analyzed case was a building located in Kraków, erected in 1971 using the WUF-T large-panel system (Warsaw Universal Form—Typical). This building represents a significantly larger-scale large-panel development compared to the first case study, which is reflected in its functional and structural parameters. The building consists of 11 above-ground storeys, has a height of approximately 31.9 m, and a total length of 162 m. It contains 264 residential units with a total usable floor area exceeding 12,900 m². The applied WUF-T technology is based on prefabricated reinforced concrete elements, in which the primary structural role is performed by transverse load-bearing walls arranged in a regular modular grid. This solution enabled rapid assembly of buildings and standardization of apartment layouts; however, at the same time, it introduced significant limitations regarding future reconstruction and adaptation possibilities. Due to its scale, applied technology, and the extent of previous modernization measures, the building constitutes a representative example

of large-panel housing complexes, in which the modernization process is particularly complex and requires consideration of both technical and organizational aspects.

Table 1. Characteristics of the analyzed large-panel buildings [13–17].

ID	Location	Year of Construction	Technology/System	Building Scale	Structural System	Scope of Previous Modernization Measures	Main Problems
A	Rzeszów	1979	RKL P-73	small scale (5 storeys)	prefabricated load-bearing walls, transverse structural layout	roof insulation, partial window replacement, modernization of selected installations	lack of comprehensive modernization, thermal bridges, outdated technical systems
B	Kraków, Opolska Street	1971	WUF-T	large-scale (11 storeys, 264 apartments)	prefabricated load-bearing walls, modular system	thermal insulation of external walls	large scale hindering modernization, lack of integration between technical systems and renewable energy sources
C	Kraków, Szafirowa Street	approx. 1990	WUF-GT 84	medium scale (commercial and residential functions)	frame-panel structural system	thermal renovation (insulation of building envelopes)	partial modernization, energy performance limitations
D	typical buildings in various cities	1970s–1980s	W-70	diversified	prefabricated load-bearing walls, high degree of standardization	partial modernization measures (various scope) diversified	functional limitations, adaptation difficulties, thermal bridges limited design flexibility, technological limitations, varying modernization potential
E	various locations	1960s–1980s	OWT, Szczecin system, regional systems	diversified	open systems, closed systems, various structural solutions		
F	Krosno	1977	RWP-73 (Rzeszów Large Panel System, regional system)	medium-scale (5 above-ground storeys with basement, 4 staircase cores)	prefabricated load-bearing walls, high degree of standardization	moisture and thermal insulation of the basement; insulation of external walls in 2014 combined with strengthening of the façade texture layer	lack of comprehensive modernization, thermal bridges, outdated building service systems

The third building, also located in Kraków, was constructed at the turn of the 1980s and 1990s and represents a larger-scale multi-family development with a commercial ground floor and residential functions on the upper storeys. The building was constructed using the WUF-GT 84 frame-panel system with the use of prefabricated structural elements and monolithic supplementary components.

The fourth analyzed group of buildings consists of buildings constructed using the W-70 system, which was one of the most widely applied large-panel systems in Poland. These buildings are characterized by a repetitive structural arrangement based on prefabricated load-bearing walls and a modular design grid. A high degree of industrialization of

the construction process can be observed in these buildings, including prefabrication of installation elements such as sanitary cabins. At the same time, such a high level of standardization significantly limits the possibilities for functional transformation of these buildings.

As a fifth group of large-panel buildings, data from OWT-67 and the Szczecin system, as well as selected regional systems, were considered. These systems differ in terms of openness, the number of prefabricated elements, and possibilities for shaping apartment layouts. Descriptions of these technologies emphasize that closed systems are characterized by a limited number of prefabricated elements, resulting in lower design flexibility, whereas open systems allow for greater diversity of architectural and functional solutions. These analyses constitute an important complement to the case studies, enabling the identification of systemic modernization limitations resulting directly from the adopted prefabrication technology.

An additional analyzed case is a building located in Krosno, constructed using the regional RWP-73 system (Rzeszów Large Panel System) and commissioned in 1977. This building represents a medium-scale development (five above-ground storeys with a basement and four staircase cores) and a high degree of structural standardization characteristic of regional systems. The structure is based on prefabricated load-bearing walls, which—similarly to the other analyzed cases—limits the possibilities for modifications of the functional layout and modernization of technical systems. In the past, partial modernization measures were implemented in the building, including moisture and thermal insulation of the basement and thermal insulation of external walls (2014), together with strengthening of the façade texture layer.

In the analyzed buildings, various modernization measures implemented in the past were identified, including insulation of flat roofs, replacement of windows and doors, modernization of selected technical systems, and partial improvement of the thermal insulation performance of building envelopes. However, these measures were generally fragmented in nature and were not preceded by a comprehensive energy analysis, which limited their effectiveness in the context of contemporary requirements.

Cases A, B, C and F represent individual buildings subjected to detailed analysis, whereas cases D and E refer to broader groups of buildings and typological categories used to complement the interpretation of modernization barriers observed in practice. The analyzed buildings represent a diversified stock of large-panel buildings in terms of scale, applied technology, and the scope of previously implemented modernization measures. This comparison enables the identification of recurring modernization problems and the assessment of their impact on the adaptation of large-panel buildings to EPBD requirements.

The relationships between the identified technical, functional, organizational, and energy-related limitations and the subsequent modernization decision-making process are summarized in Figure 2. The framework illustrates the sequence of activities from building diagnosis and identification of modernization barriers to the selection of renovation measures and assessment of compliance with EPBD requirements.

4.2. Limitations and Problems Resulting from Previous Partial Modernization Measures

The modernization of large-panel buildings in Poland constitutes a complex challenge resulting from their specific structural characteristics, as well as technical, organizational, and economic conditions. The relationships between these factors and the modernization decision-making process are presented in Figure 2. In the context of the requirements of the Energy Performance of Buildings Directive (EPBD), particular importance is attached to the

implementation of comprehensive modernization measures, which, however, encounter numerous significant barriers.

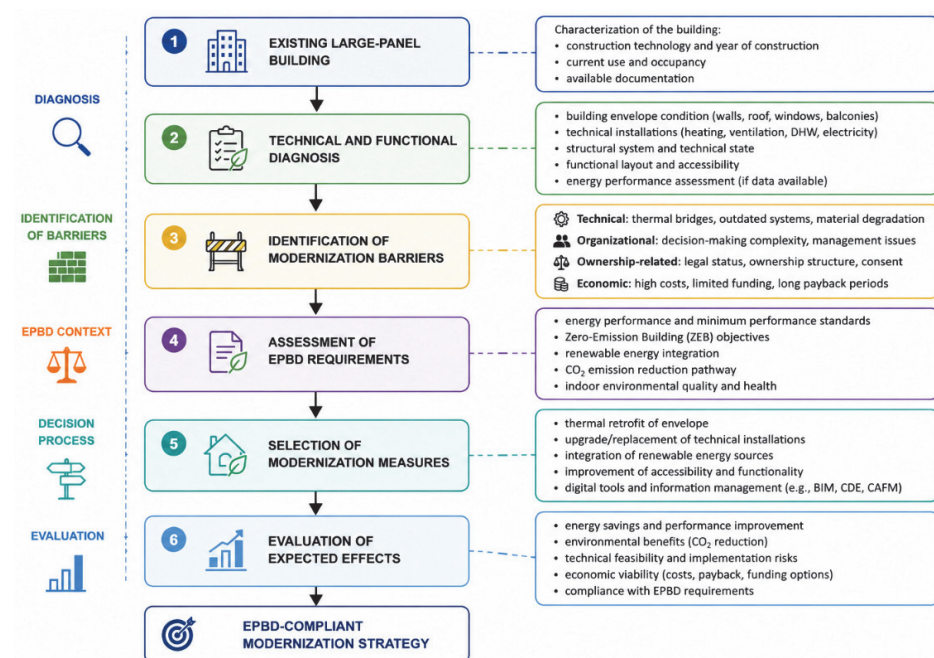


Figure 2. Framework for identifying modernization barriers and selecting renovation measures for large-panel residential buildings in relation to EPBD requirements. Source: authors' own elaboration.

4.2.1. Low Energy Performance of Building Envelopes

The most frequently identified technical problem is the low energy performance of external building envelopes. This results from their structural characteristics, including thin insulation layers and the high thermal conductivity of reinforced concrete elements. In the analyzed cases, the thermal transmittance coefficient of walls after previous modernization measures was approximately $0.295 \text{ W}/(\text{m}^2 \cdot \text{K})$, which does not meet the current requirements of $0.20 \text{ W}/(\text{m}^2 \cdot \text{K})$. This indicates that a significant proportion of the thermal modernization measures implemented in the past are insufficient considering current regulations. An important recurring problem identified in the analyzed buildings was also (Table 2):

- thermal bridges resulting from the prefabricated structural system [8,11]
- discontinuities in thermal insulation (e.g., mounting grids, balconies),
- the application of outdated insulation systems without comprehensive energy analysis.

Table 2. Relationship between the identified low energy performance issues, the analyzed buildings, and the requirements of the EPBD directive.

Problem	Building	Nature of the Problem	Technical and Energy-Related Consequences	EPBD Requirements
Thermal bridges at prefabricated element joints	A, B, D, F	discontinuities in insulation, panel connections, balconies	increased heat losses, deterioration of energy performance	improvement of building energy performance, reduction of energy losses
Low thermal insulation performance of building envelopes	A, B, C, D, F	insufficient insulation thickness, outdated material solutions	high heating energy demand	compliance with current energy requirements, reduction of energy consumption

Table 2. *Cont.*

Problem	Building	Nature of the Problem	Technical and Energy-Related Consequences	EPBD Requirements
Lack of integration of renewable energy sources	all	absence of PV (Photovoltaic) systems, heat pumps, hybrid systems	inability to achieve the ZEB standard	integration of renewable energy sources, transition towards zero-emission buildings
Fragmented (“shallow”) modernization	A, C, F	modernization limited to selected elements (e.g., façades)	limited improvement in energy performance, necessity for repeated renovation works	implementation of comprehensive modernization (deep renovation)
Outdated technical systems	A, B, C, F	low efficiency of heating and ventilation systems	high energy consumption, lack of system control	modernization of building technical systems
Structural limitations	B, D	load-bearing wall arrangement, high degree of standardization	limited possibilities for reconstruction and installation modernization	necessity to adapt modernization strategies to the existing structural system
Functional limitations	A, B	outdated apartment standards, lack of accessibility	reduced user comfort, adaptation difficulties	improvement of the functional quality of buildings (indirectly, within the context of sustainable construction)
Building scale	B	large number of apartments, complex management structure	organizational and investment-related difficulties	increasing modernization efficiency at the level of entire building stocks
Diversity of prefabrication systems	D, E	different technologies (OWT, W-70, regional systems)	lack of universal modernization solutions	necessity for an individual approach to renovation

In many buildings:

- thermal insulation measures were implemented in accordance with former standards, but are currently insufficient,
- modernization efforts focused mainly on façades while neglecting technical systems and ventilation,
- no comprehensive energy diagnostics were conducted, which prevented the identification of key problems and the selection of the most effective modernization solutions.

Table 2 summarizes the relationships between the identified modernization barriers, their technical and energy-related consequences, and the requirements introduced by the EPBD directive.

One of the fundamental problems in achieving the required level of energy performance, including the Zero-Emission Building (ZEB) standard, is the presence of structural limitations characteristic of prefabricated construction. Large-panel buildings were constructed using systems with diversified material and structural solutions, which affects both their current technical condition and their modernization potential. Studies indicate that, despite the passage of time, most buildings maintain an adequate level of structural safety; however, the connections between prefabricated elements, including vertical and horizontal joints, remain of key importance and may constitute the weakest points of the structure [8,10,11]. The limited possibility of interference with the load-bearing structure, resulting from the adopted static scheme, hinders the implementation of more advanced functional and installation-related transformations.

Previous modernization measures, focused mainly on the thermal insulation of external walls, often did not include comprehensive improvement of the overall energy performance of the building. These problems are further aggravated by the technical condition of internal installations, including heating and ventilation systems, which are outdated and energy inefficient [18]. In many cases, there is also a lack of integration of renewable energy sources, which additionally hinders compliance with the standards required by the EPBD directive, including the zero-emission building standard.

As a result, situations occur in which a building has formally undergone thermal modernization but still does not meet current energy requirements, while repeated modernization generates additional costs and technical difficulties. In the context of the EPBD, this implies the necessity of moving from “superficial” thermal retrofits towards a comprehensive approach involving the elimination of thermal bridges and modernization of the entire building envelope. Consequently, achieving high energy performance requires comprehensive measures extending beyond standard thermal modernization [19].

4.2.2. Installation and System-Related Problems of Large-Panel Technology

A continuation of the identified limitations resulting from previous modernization measures are problems related to building service systems, which in many cases were not included within the scope of the performed modernization works. In the analyzed buildings, the condition of central heating and domestic hot water systems was identified as diversified and often requiring repair or replacement, which negatively affects the energy performance of the entire building.

Heating, sanitary, and electrical installations are characterized by a shorter life cycle and require periodic replacement or modernization in accordance with applicable regulations and technical requirements. In many buildings, the parameters of electrical installations do not comply with contemporary technical requirements or the increasing demand for electrical power [20]. Their technical condition has a direct impact on operational safety, including fire safety, which makes their modernization an important component of comprehensive renovation measures. In practice, however, modernization of installations in large-panel buildings is often limited or postponed, mainly due to the necessity of carrying out works at the level of the entire building rather than individual apartments, as well as organizational and financial difficulties.

An additional problem is the lack of modern ventilation systems, particularly mechanical ventilation with heat recovery, which leads to increased energy losses and deterioration of indoor air quality. In many cases, gravity ventilation systems are still in operation, whose effectiveness is limited and dependent on external conditions. An important limitation is also inefficient heat distribution resulting from outdated installation solutions and the lack of system regulation. In the context of the EPBD requirements, this implies the necessity for comprehensive modernization of building technical systems, including heat sources, distribution systems, and ventilation systems.

4.2.3. Functional and Accessibility Limitations

An important issue, often overlooked in the modernization process, concerns the functional limitations of large-panel buildings. These result from the design standards adopted during the period of their construction and the high degree of standardization of the applied solutions. The case studies identified, among others:

- excessively narrow stair flights that do not comply with current requirements,
- the absence of elevators in low-rise buildings,
- inflexible apartment layout solutions,
- limited accessibility of common areas for persons with special needs,

- the necessity of adapting apartments for persons with disabilities (e.g., access to bathrooms and toilets, removal of thresholds between rooms, inadequate room dimensions),
- the absence of vestibules at building entrances,
- low acoustic insulation performance of internal partitions.

Improvement of these parameters is, in many cases, hindered by the necessity of interfering with the building's structural system, as well as by limitations resulting from current technical and construction regulations. The case studies also revealed numerous inconsistencies with current technical requirements and regulations concerning building operational safety. These relate in particular to:

- deficiencies in fire protection systems (e.g., insufficient smoke extraction, lack of required equipment),
- improper parameters of stairs and handrails,
- insufficient lighting of circulation routes.

These problems do not result directly from structural degradation but are consequences of regulatory changes, increasing user requirements, and the aging of technical infrastructure. In practice, this means the necessity of simultaneously adapting buildings to current safety standards, which was often not considered in previous modernization measures. In relation to the requirements of the EPBD directive and the principles of sustainable construction, this implies the need to combine energy modernization with improvements in the functional quality of buildings, which, however, increases the complexity of the entire investment process.

4.2.4. Other Limitations

The possibilities for comprehensive modernization of large-panel buildings in the context of EPBD requirements, including the primary objective of achieving the Zero-Emission Building (ZEB) standard, depend on the structural and technological system of the large-panel construction. Open systems (e.g., OW-T) and closed systems (e.g., the Szczecin system) can be distinguished.

Buildings constructed using closed systems are generally characterized by greater limitations regarding interference with the structural layout and functional reconstruction. However, this does not mean a complete lack of adaptation possibilities—in practice, many transformations can be carried out within the internal layouts, provided that structural safety principles are maintained. Therefore, the assessment of modernization potential should consider both the type of prefabrication system and the specific design solutions of a given building.

Open systems, although also limited by the prefabricated nature of the structure, demonstrate greater adaptation potential, which may facilitate the implementation of comprehensive modernization measures in relation to the requirements of the building directive. Nevertheless, regardless of the system type, achieving the ZEB standard in existing large-panel buildings requires a comprehensive approach involving modernization of building envelopes, technical systems, and energy sources. The type of prefabrication system influences the scope of possible measures and the level of difficulty associated with their implementation.

In non-renovated large-panel buildings, problems also occur with regard to parameters covered by acoustic requirements. These are caused, among others, by various air leakages and increased normative requirements concerning the acoustic insulation performance of building partitions [6]. Comprehensive thermal modernization improves certain acoustic properties, particularly of external walls due to window replacement. However, improvement of acoustic comfort within the building requires modernization of floors and inter-apartment walls.

Indoor air pollution identified in studies conducted by the Building Research Institute (ITB), caused by the incorporation of materials—mainly finishing materials—emitting harmful chemical substances, is currently being eliminated during renovation works through the application of modern materials ensuring good indoor air quality in apartments [6,7].

The modernization process also encounters significant organizational and legal barriers [21]. A characteristic feature of the Polish large-panel housing stock is its fragmented ownership structure, including housing cooperatives and condominium associations, which significantly complicates investment decision-making processes. The process of agreeing on the scope of modernization, financing methods, and selection of technical solutions is often lengthy and burdened with the risk of conflicts between apartment owners. Additionally, formal and administrative limitations related to applicable regulations, procedures, and technical requirements may prolong and complicate the investment process. As a result, even technically justified modernization measures are not always implemented in practice [22].

Another important group of limitations concerns economic conditions. Comprehensive modernization of large-panel buildings involves high investment costs, which often exceed the financial capabilities of building owners or managers [23–25]. The availability of support instruments, such as subsidies or preferential loans, plays an important role in the implementation of such projects; however, their scope and conditions are not always sufficient. An additional problem is uncertainty regarding investment profitability, resulting, among others, from long payback periods and fluctuations in energy prices. Consequently, decisions concerning comprehensive modernization are often postponed or limited to measures of smaller scope.

5. Synthetic SWOT Analysis of the Modernization Potential of Large-Panel Buildings

Based on the conducted case study analyses and literature review, a synthetic SWOT matrix was developed (Table 3) to assess the modernization potential of large-panel buildings in the context of the requirements of the EPBD directive. This analysis constitutes a supporting tool for identifying relationships between technical, organizational, and economic conditions, as well as their impact on the possibilities of adapting the existing building stock to contemporary energy and environmental standards.

Table 3. SWOT analysis of the modernization potential of large-panel buildings.

Strengths		Weaknesses	
1	Large stock of existing residential buildings with significant social importance	1	Limited possibilities for achieving the Zero-Emission Building (ZEB) standard
2	Relatively high structural durability and possibility of continued operation	2	Limited possibilities for improving internal building logistics (limited technical possibilities for elevator installation and/or very high associated costs)
3	Favorable location (access to technical and social infrastructure)	3	Low thermal insulation performance of building envelopes and occurrence of thermal bridges
4	Possibility of implementing thermal modernization measures	4	Outdated technical systems (heating, ventilation, electrical installations)
5	Potential for the use of flat roof areas and housing estate spaces for renewable energy systems	5	Limited possibilities for improving apartment functionality
6	Potential use of Building Information Modeling (BIM) for integration of technical, energy-related, and operational data in the modernization process [26]	6	Existing partial thermal modernization of building envelopes complicates repeated comprehensive modernization

Table 3. Cont.

Strengths		Weaknesses	
		7	Lack of up-to-date and coherent digital documentation of the existing building stock
Opportunities		Threats	
1	Availability of financial support programs (subsidies, tax incentives, loans)	1	High costs of comprehensive modernization
2	Development of new technologies and materials improving energy performance	2	Technical limitations resulting from prefabrication technology
3	Increasing importance of climate policy and EPBD requirements	3	Organizational difficulties resulting from fragmented ownership structures
4	Compact apartment layouts contributing to reduced energy consumption per unit area	4	Necessity of carrying out works without relocating residents
5	Increasing demand for housing within the existing urban building stock	5	Risk of investment unprofitability due to long payback periods
6	Development of digital tools (BIM, CDE, digital twins) supporting planning and optimization of deep renovation	6	High costs and complexity of BIM model development for existing buildings (inventory surveys, data updating)

The SWOT matrix was developed based on the previously identified modernization problems, the characteristics of the large-panel building stock, and the regulatory requirements arising from the European Union's climate policy. Both internal factors (strengths and weaknesses resulting from the technical and functional characteristics of the buildings) and external factors (opportunities and threats related to market, regulatory, and technological conditions) were considered. The identified factors were classified into strengths, weaknesses, opportunities, and threats according to their origin (internal or external) and their potential impact on the modernization process. The SWOT analysis was applied as a qualitative tool for synthesizing the findings obtained from the case studies and literature review. Individual factors were included in the matrix when they were repeatedly observed across the analyzed cases and/or consistently identified in the literature as relevant determinants of the modernization of large-panel buildings in the context of EPBD implementation.

The SWOT analysis indicates that large-panel buildings possess significant modernization potential, resulting primarily from their scale, structural durability, and favorable location within urban structures. These factors make this building stock potentially important in the process of the energy transition of the building sector. At the same time, the identified weaknesses are systemic in nature and include both technical limitations (thermal bridges, outdated technical systems, limited structural flexibility) and functional limitations. A particularly significant problem is the low effectiveness of previous modernization measures, which were often fragmented and did not include a comprehensive approach.

The identified opportunities are primarily related to the increasing importance of climate policy and the availability of financial support instruments, which may significantly accelerate the modernization process. The development of new technologies, including renewable energy solutions and energy management systems, increases the possibilities for improving the energy performance of existing buildings [25,27]. On the other hand, major threats include high investment costs and technical limitations resulting from the applied prefabrication systems. Additionally, organizational conditions—particularly fragmented ownership structures—remain a significant barrier hindering investment decision-making processes. In practice, this means that even under favourable external

conditions, the implementation of comprehensive modernization measures may remain significantly constrained.

Building Information Modeling (BIM) may support future modernization processes of large-panel buildings. BIM may facilitate information management, renovation planning, and the evaluation of alternatives to modernization. The potential role of BIM in supporting future modernization processes was identified; however, its practical application was not investigated within the scope of the present study [26]. This technology enables the integration of data concerning the structure, technical systems, and energy performance characteristics of a building, allowing variant analyses and optimization of modernization measures from the perspective of the building life cycle. In relation to the requirements of the EPBD directive, it should be emphasized that effective modernization of large-panel buildings requires a systemic approach integrating technical, organizational, and economic activities. Of key importance is the transition from fragmented modernization measures towards comprehensive solutions based on reliable diagnostics and a long-term building stock management strategy.

In the context of existing large-panel buildings, the practical implementation of BIM-based approaches would require the integration of archival documentation, technical surveys, energy audit data, and information collected during operation. Such datasets could support renovation scenario development, energy performance assessment, and long-term information management throughout the building life cycle.

6. Conclusions

The analysis of large-panel building case studies indicates that one of the key modernization challenges is the structural, technological, and operational diversity of these buildings in the context of achieving the objectives of the Energy Performance of Buildings Directive (EPBD). The analyzed buildings were constructed using various prefabrication systems (including OWT, WUF-T, and RKL P-73), differing both in structural layout and in the parameters of building envelopes and technical systems. In addition, construction quality strongly depended on the implementation stage—from prefabricated element production, through transport and assembly, to building operation. As a result, even buildings constructed within the same prefabrication system may exhibit different technical problems and renovation requirements. From the perspective of the EPBD, this means that uniform modernization strategies cannot be applied, and an individual approach based on diagnostics of a specific building is necessary. This applies in particular to the assessment of possibilities for functional transformation, which do not result solely from the classification of the prefabrication system but also depend on detailed design solutions and the extent of interference with structural and installation elements. In practice, this means that the modernization potential of this building stock should be considered at the level of individual buildings rather than solely on the basis of general characteristics of the system.

The contribution of this study lies not in the identification of previously known technical deficiencies of large-panel buildings, but in their interpretation within the framework of the revised EPBD directive requirements and the assessment of their implications for future modernization strategies. Because of the exploratory nature of the study and the qualitative character of the analyzed material, the findings should be interpreted as indicative of recurring modernization barriers rather than as statistically representative results for the entire large-panel building stock.

Despite numerous limitations, the conducted analyses indicate a significant modernization potential of large-panel buildings. In particular, it is possible to substantially reduce energy consumption—typically by 30–60% and, in the case of deep renovation

measures, by more than 60%—through the implementation of comprehensive modernization strategies [22–25,27]. The identified modernization barriers are derived from the analyzed case studies, whereas the reported energy-saving potentials are based on findings available in the literature. Comprehensive thermal modernization leading to improved energy performance is also associated with the elimination of other unfavorable phenomena occurring in these buildings, such as poor acoustic performance of partitions and inadequate hygienic and health-related conditions, including indoor air quality. Modernization may also contribute to improved user comfort and increased market value of buildings. An important direction of modernization activities is the integration of renewable energy sources and energy management systems, which is consistent with the requirements of the EPBD directive. However, achieving these effects requires:

- a comprehensive approach to modernization (so-called deep renovation),
- implementation of measures based on reliable technical and energy diagnostics,
- coordination of structural, installation-related, and functional interventions.

Failure to meet these conditions may result in repetition of the mistakes of previous modernization measures and limit the possibility of achieving the required energy performance standards. The findings of this study have implications for several stakeholder groups. For researchers, they highlight the need for further investigations into integrated modernization methodologies, including the application of digital tools and Building Information Modeling (BIM) in renovation planning and decision support [25–28]. For practitioners, the results emphasize the importance of adopting a comprehensive approach that combines energy-related, technical, organizational, and functional aspects of building modernization. For policymakers, the findings underline the necessity of developing financial and organizational support mechanisms that facilitate the implementation of EPBD requirements within the existing residential building stock.

This study has several limitations. Limited access to detailed energy, operational, and economic data from housing cooperatives and property managers prevented the performance of quantitative analyses and the assessment of modernization effects using uniform indicators. Consequently, the study adopted a qualitative case study approach focused on identifying technical, organizational, and legal barriers affecting the implementation of EPBD requirements rather than on the quantitative evaluation of modernization outcomes.

The results of the conducted analyses indicate the need for further research concerning the integration of technological, organizational, and digital solutions in the modernization process of existing prefabricated residential buildings, which may constitute an important development direction in the context of achieving the climate objectives of the European Union. In the context of the growing importance of data-driven approaches, digital tools identified in the SWOT analysis as opportunities—particularly Building Information Modeling (BIM)—may play a significant role in the modernization process by enabling integration of building-related information and supporting modernization decision-making processes. Their application may contribute to increased efficiency of investment planning and reduction of design-related risks; however, this requires solving the problem of data availability and updating for existing buildings.

Future research should include quantitative analyses based on detailed energy, operational, and economic datasets. Particular attention should be paid to Life Cycle Cost (LCC) analyses and cost-effectiveness assessments of alternative modernization scenarios for large-panel buildings, enabling a more comprehensive evaluation of both technical and economic aspects of compliance with EPBD requirements.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modeling
CAFM	Computer-Aided Facility Management
CDE	Common Data Environment
CO ₂	Carbon dioxide
EPC	Energy Performance Certificate
EPBD	Energy Performance of Buildings Directive
GUS	Statistics Poland (Główny Urząd Statystyczny)
ITB	Building Research Institute (Instytut Techniki Budowlanej)
PV	Photovoltaic
ZEB	Zero-Emission Building

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