Region-Focused Architectural Design in the Context of the Circular Economy

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Abstract. The transition of the construction industry towards the principles of the circular economy is regarded as one of the key areas for ensuring the sustainable development of the urban environment. In industrial regions, the issue of reusing existing industrial buildings is of particular relevance, as these can be viewed as a significant resource for secondary building systems. One promising approach is the concept of 'urban mining', which involves the use of material resources accumulated within the urban environment. However, in most studies, urban mining is viewed primarily as a tool for analyzing material flows, whilst its potential as a strategy for architectural design remains insufficiently explored.

The aim of this study is to develop a conceptual approach to regionally-oriented architectural design based on the integration of circular economy principles and the utilization of the potential of the industrial building stock. The research methodology includes an analysis of the scientific literature, a structural-typological analysis of industrial building systems as well as methodological modelling at the intersection of regional planning and architectural design. The research has identified architectural principles and design tools that enable the integration of circular economy strategies into the transformation processes of industrial territories. A conceptual model is proposed for utilizing the industrial building stock as a spatially organized resource for secondary structural systems, and has been tested using a case study of a facility reorganization. The findings expand architectural approaches to implementing circular economy principles and can be applied in the development of strategies for the regeneration of industrial regions.

Keywords: Circular economy · Urban mining · Regional architectural design

1 Introduction

As urbanization accelerates and natural resources are consumed at a growing rate, the construction sector is becoming a critical component of urban environmental sustainability. It is evident that the construction sector has a high resource intensity - consuming up to 40% of natural resources and energy [6], as well as the lack of a unified conceptual model for implementing the circular economy. This reinforces the need to transition

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from linear models to circular economic principles [7]. Among the promising areas is urban mining. This views the existing urban environment as a source of secondary resources accumulated in buildings, infrastructure and engineering systems. According to industrial ecology, circular economies are analogous to natural ecosystems with closed material and energy flows. In a study developed by [8], many key principles of the circular economy - systems thinking, resource efficiency, and circularity - are derived from industrial ecology.

The importance of sustainable and adaptive architectural solutions has been highlighted in research on regional architecture in Kazakhstan. G.S. Abdrasilova and L.M. Aukhadiyeva [9] note that the contemporary development of the country's architecture is closely related to the implementation of sustainable design principles. It includes the adaptive reuse of buildings and the development of a national aesthetic identity. These approaches form the basis for integrating urban mining into the architectural design of industrial regions. Regional studies highlight the importance of taking into account the economic, social, natural, climatic, and historical and cultural conditions of a region's development [10, 11], since these studies constitute the basis of a practice-oriented methodological framework for implementing circular economy principles and urban mining in the architectural design and management of material resources in industrial regions.

The authors believe that the integration of circular economy principles into the architectural design of industrial areas is possible through the development of regionally adapted design strategies, which utilize the existing industrial building stock as an urban mining resource and use design tools for the regeneration of industrial areas as an urban mining resource. This hypothesis defined the objective of the study, which is to develop a methodological strategy for the renovation of industrial facilities that takes regional characteristics into account. According to the stated research objective, the following research questions are formulated:

In what ways can the principles of the circular economy be incorporated into regional architectural design at industrial facilities?

What potential does the existing industrial building stock hold as a source of secondary resources?

What architectural and design tools are available to facilitate the integration of circular economy principles into industrial site regeneration programs?

The answers to these research questions formed the basis for the development of a methodological strategy aimed at improving resource efficiency, reducing environmental impact, and creating a sustainable architectural environment in Kazakhstani industrial regions.

2 Literature Review

According to Guerra et al. [12], a systematic review of over 300 publications, circular construction is still at its infancy and focuses primarily on waste management and material reuse. Finamore and Oltean-Dumbrava [6] highlight the lack of a single definition of the circular economy in relation to construction and stress the need for a holistic approach that encompasses the entire building value chain. There is also a need for a

comprehensive approach that considers all aspects of building life cycle management, including design, operation, renovation, and demolition [13, 14].

The integration of circular economy principles into the construction sector is primarily focused on the management of construction and demolition waste. The bibliographic analysis by Hasibuan G. et al. [15] examines the main research areas related to the use of circular economy principles in the management of construction and demolition waste, as well as sustainable engineering practices in buildings.

A number of academic publications have addressed the methodology of circular architectural and construction design in the past 10–15 years. In the present day, frameworks for strategies integrating circularity principles into a design object's life cycle are being developed most actively, including the formulation of revised requirements for architects' professional competencies [16–18], as well as assessment methodologies and indicators of building circularity [19] and industrial areas [20]. An approach to territorial and regional planning of industrial areas is defined by the circular economy. The method replaces linear location factors with closed cycles that are intended to produce "economic symbiosis." A number of modern industrial areas are already designed to function as ecosystems based on resource distribution and regional specificities [20, 21]. As part of this effort, circular revitalization practices are being implemented in old or degraded industrial areas [22]. Despite an increasing number of publications, the spatial aspects of circular economy implementation at the regional level remain largely unexplored. Several researchers report that studies have been limited in scope, particularly because the spatial organization of industrial territories is fragmented and there are no standardized circular economy indicators at the regional level [10, 11].

The literature on spatial aspects and regional planning of industrial areas in Kazakhstan has not yet addressed these issues. In the research, the macro-region is represented by issues of the circular economy at the sectoral, management, or entrepreneurial levels [23, 24], without addressing territorial and industrial planning at the regional level. The Republic of Kazakhstan has formed a comprehensive database of strategic documents [1–4], focused on the consistent widespread implementation of the principles of sustainable development and green economy. Key government initiatives and regulations, from the long-term strategy "Kazakhstan – 2050" [1] to the Environmental Code of the Republic of Kazakhstan [3] and international climate obligations [4], create institutional conditions for the transition to circular architectural and construction practices. At the same time, the analysis of the current design regulatory documentation of industrial facilities [32–35] shows that the concept of urban mining has not yet been properly reflected and applied in practice.

The authors of this article have attempted to contribute to the growth of research on regional planning of industrial territories in the context of the circular economy by filling a part of the research gap. Ust-Kamenogorsk, a city with a history of metallurgy and environmental problems, has been used as an example. This study aims to develop a circular economy-based planning strategy. With this approach, it is possible to enhance the sustainability of industrial zones, optimize resource use, and revitalize territories while taking into consideration local specificities.

3 Methods and Materials

A hybrid methodology was selected due to the interdisciplinary nature of the research topic, which is situated at the intersection of concepts relating to the circular economy, urban mining, architectural and urban design, and spatial planning. This article utilized a systematic qualitative analysis of scientific literature and regional strategic documents in conjunction with a deductive-inductive approach in identifying the criteria, characteristics, and parameters associated with circular design in addition to a structural-typological analysis of industrial facilities and an analysis of these results based on regional considerations (Fig. 1).

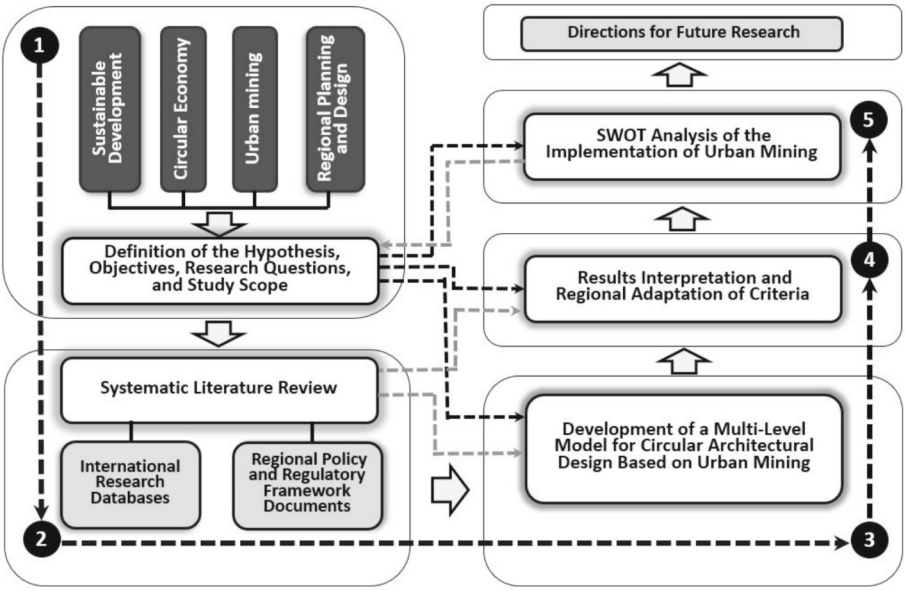

Fig. 1. Research methodology.

The study comprises five main stages:

In the first stage, the development of a conceptual framework will include the clarification of terminology, the formulation of a hypothesis, and the formulation of research questions;

The second step is to conduct a systematic review of sources based on keyword searches and analysis of scientific literature primarily from the Scopus database. A search for the following keywords and combinations thereof was conducted: “circular economy”, “urban mining”, “industrial sites”, “industrial buildings”, “regional planning”, “regional design”, “sustainable local development”, “architectural design”, “local architectural design”. According to the most comprehensive search, only two articles were found, requiring the search parameters to be widened. Duplicate articles and those with relevant titles were excluded from the various combinations. After analyzing the abstracts, a selection was made. A total of 30 articles were selected for publication.

Almost all restricted access publications were excluded from the search; these were analyzed at the abstract stage. The keywords and context of strategic regional documents were also analyzed;

At the third stage, a multilevel model of circular architectural design is developed based on urban mining within territorial boundaries and the typological boundaries of "city" and "building". In this study, approaches, indicators, metrics, and their application in regional design were identified through a deductive-inductive analysis of existing research.

In the fourth stage, the model's structure was substantiated by interpreting the results in relation to the regional context. The strategy's key levels and the mechanism for implementing it should be defined, the main indicators of regeneration should be described, conduct a pilot study and conclusions drawn re-garding the feasibility of implementing these indicators in Kazakhstan's regional context.

Stage five consists of a SWOT analysis, which enables the integration of urban mining into industrial area planning, as well as providing a structured framework to plan strategies for the sustainable development of the city.

The empirical subject of the study is the city of Ust-Kamenogorsk - one of the largest industrial centers in Eastern Kazakhstan, which has a historically established industrial structure. Many of the studies examined cities that are developing according to a circular planning strategy [25, 26].

While there are numerous environmental initiatives and sustainable development projects in Ust-Kamenogorsk, it has not yet achieved full status as a circular industrial city model. Despite the existing resources, industrial buildings, and well-developed engineering infrastructure, as well as the presence of active stakeholders as scientists and technicians at the technical university, the implementation of an international educational project on the circular economy provides the opportunity for the implementation of sustainable strategies, such as the use of urban mining principles, the reuse of building materials, and the regeneration of waste sites.

Almost all sectors of industry are represented in the city, including mining, metallurgy, mechanical engineering, manufacturing, light industry, food industry, energy production, and large-scale infrastructure. In the region, industrial production accounts for 77.2% of the total production. In 2024, the industrial output is expected to increase from 2.1 trillion tenge to 3.9 trillion tenge by 2030, as a result of reconstruction and modernization, along with the opening of new workshops and factories [5].

Ust-Kamenogorsk has a substantial industrial base, which was established primarily between 1940 and 1980. In the 1990s, the economic crisis led to the closure of production facilities, resulting in the emergence of abandoned production facilities. In the subsequent years, some sites have been partially restored or repurposed for other purposes, while others remain vacant. Presently, industrial areas constitute 13.2% of the total area of the city, of which approximately 2.3% is unused (Fig. 2). As the mining and metallurgical sector - the city's main economic driver - declines, significant modernisation and regeneration of industrial areas may also be necessary.

The legacy of these buildings has resulted in the development of an extensive stock of industrial buildings, ancillary structures, standardized warehouses, and mass-produced

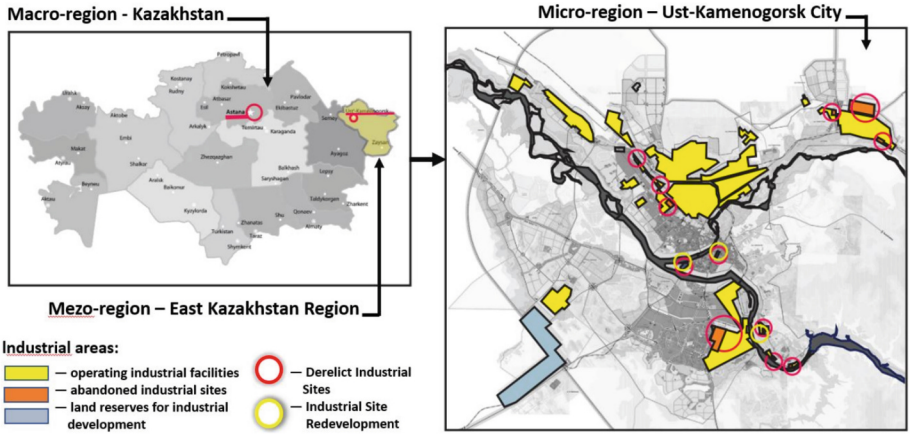

Fig. 2. Regional context of the study.

prefabricated structures. An analysis of the local building stock revealed that the structures of the region's industrial buildings consist of structural systems consisting of reinforced concrete frames, steel frames, panels, floor slabs, and flat systems made of bricks and blocks, in addition to long-span structures which form the spatial framework of industrial architecture.

4 Urban Mining as a Tool for Circular Regeneration of Industrial Sites

Recent years have seen an active development in the assessment of urban mining potential within the context of circular economies and sustainable construction. This assessment is based on analysis of the material flow, the life cycle of buildings, and the spatial characteristics of urban environments. According to a number of current studies, cities continue to be viewed as anthropogenic deposits of secondary resources, primarily building materials. Accordingly, propose an assessment of the potential of urban mining by analyzing the material stock of existing buildings, the proportion of recoverable components, the level of reuse, and the environmental effects of preserving structures in order to assess the potential for urban mining [27]. In their paper, the authors emphasize the importance of quantifying circularity indicators, such as the proportion of dismantled and reused items, the content of secondary materials, as well as the reduction of carbon footprints. As Antonella Luciano and co-authors [28] demonstrate, the preservation of existing structures can significantly reduce the consumption of primary resources and greenhouse gas emissions. Contemporary research is also taking into account the spatial aspect of urban mining by analyzing the density of material stocks in the built environment, the spatial distribution of resources, and the possibility of reusing building components in circular renovations. It is important to note that urban mining is implemented at several spatial levels, from the city as a whole to the individual building, as part of the circular transformation of industrial areas. Depending on the scale, the nature

of resources managed, the decisions made, and the design tools used will differ. Figure 3 illustrates the application of urban mining at the city and building levels.

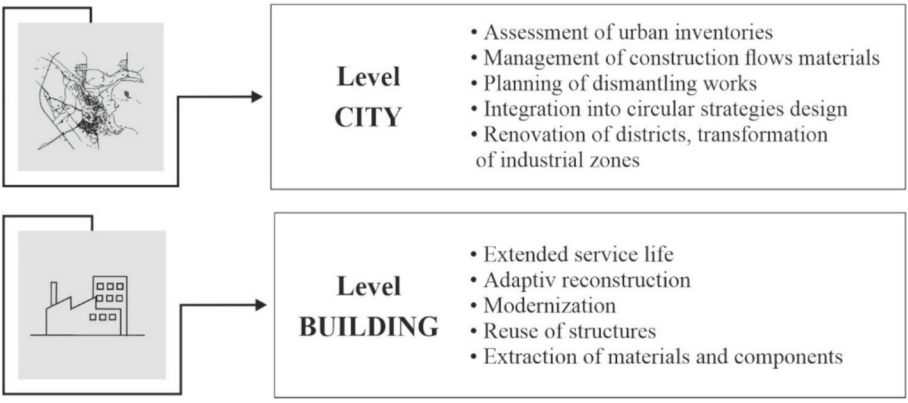

Fig. 3. Implementation of urban mining principles at the territorial and building levels of the circular transformation of the industrial environment.

In this model, the territorial material resources of an industrial city are transformed into specific architectural solutions by means of reconstruction, modernization, and reusing existing structures in order to reflect the multi-scale nature of urban mining. The findings confirm the possibility of transitioning from the assessment of urban material reserves to the design of circular buildings. The diagram serves as a basis for further examination of the levels of resources in the industrial environment.

Territories associated with industrial activity may be viewed as an interconnected system of material and spatial resources. Model is proposed, which allows the industrial environment to be viewed as a combination of territorial, structural, material, and infrastructure resources that can be integrated into circular architectural design strategies (Fig. 4).

A transition can be achieved from a regional level of materials awareness to a project level of architectural decisions through the proposed model structure. This model allows architects to interpret industrial sites as structured material banks despite the absence of quantitative GIS assessments. The system also allows architects to integrate the logic of urban resource extraction into early design stages. Research conducted by Panizza R. O. and Nik-Bakht M [27, 32]. indicates that the key resource for circular transformation is not only recoverable materials, but also the existing building stock as a whole. This requires a shift in focus from assessing individual waste streams to analyzing buildings as carriers of spatial, structural, and material resources.

In this context, the circular approach involves three stages: auditing the industrial building stock, assessing their life cycle, and modeling modernization scenarios.

Stage 1 - Identification of clusters of resources. Secondary materials may be found in industrial zones and infrastructure corridors. Structures such as reinforced concrete frames, steel trusses, prefabricated panels, and modular structural grids can be reused rather than being discarded.

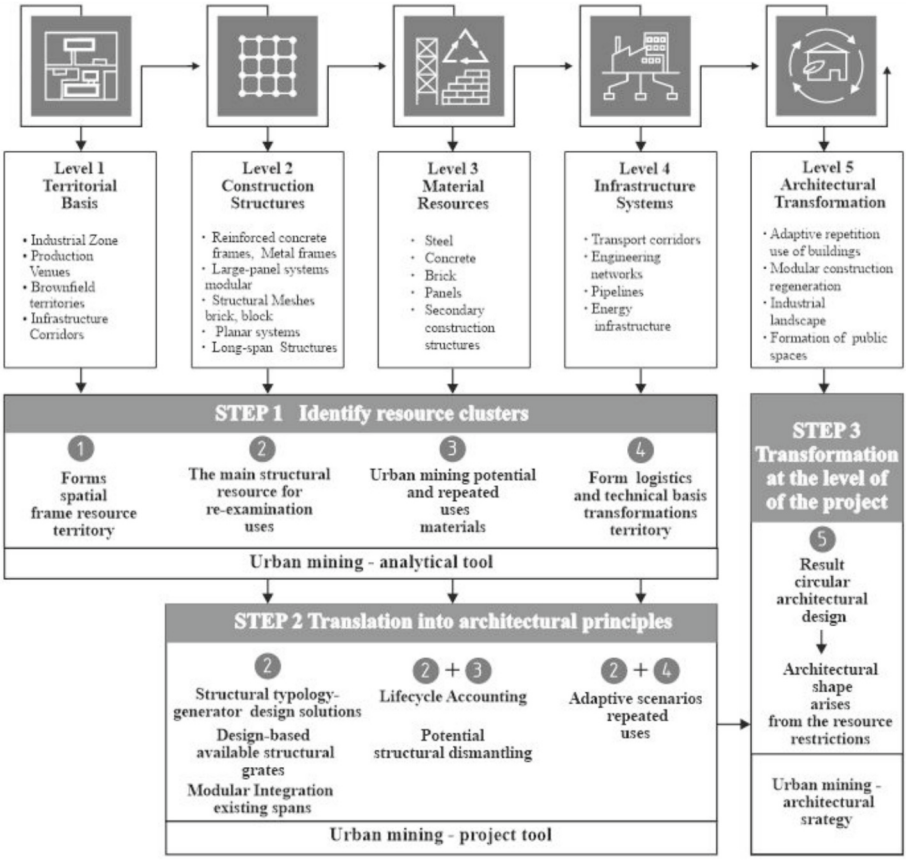

Fig. 4. A multi-level model of circular architectural design based on urban mining.

Stage 2 - Translation of the design into architectural principles.

The following principles can be applied based on the identified structural typologies:

1. Considering the life cycle of the building. The design of a structure should consider both its operation as well as its dismantling and planning for possible stages of repair, replacement, and demolition. 2. Using the available structural grids for design

3. Integrating existing spans in a modular manner. 4. Potential for structural dismantling. Identifying elements that can be reused. 5. Scenarios for adaptive reuse.

A clear division is provided in the design between structural elements that can be retained and reused and those that must be reprocessed or disposed of.

Stage 3 - Transformation at the project level. Using an industrial frame with a 6 by 6 m structural grid, for example, can serve as the spatial basis for a modular public building, where the existing load-bearing system is retained, supplemented and repurposed. The architectural form in this scenario is not the result of abstract composition, but rather of physical constraints.

A five-level hierarchy describes the spatial and material resources within an industrial site, while a three-stage circular approach outlines the sequence of how these resources are transformed into architectural solutions. It has evolved from a tool for assessing material stocks into a design generation process that integrates territorial, structural, material, and infrastructure systems into a unified framework for developing architectural solutions.

Researchers have examined a variety of approaches to reducing the resource burden associated with the construction sector, including sustainable architecture, circular design, and urban mining. Although both concepts address sustainable development, their research and practical orientations differ. Table 1 presents a comparative analysis of these approaches' key characteristics.

Table 1. Comparative analysis of circular design, urban mining and sustainable architecture.

Criterion	Circular design	Urban mining	Sustainable architecture
Main objective	Establishing closed-loop cycles for the use of materials and resources	Extracting secondary resources from the existing urban environment	Reducing the environmental impact of architecture
Scope of application	Architectural project, building systems	Urban area, material flows	Buildings, neighbourhoods, urban environments
Main subject of analysis	Life cycle of building materials and building elements	Material stocks in existing buildings and infrastructure	Energy efficiency and environmental performance of buildings
Application stage	Architectural design stage	Demolition and material recycling stage	Building design and operation stage
Architectural aspect	Integration of circular principles into architectural form and construction	Architectural aspect is considered in a limited way	Architecture is regarded as an environmentally responsible system
Type of resources used	Primary and secondary building materials	Recycled materials from existing buildings	Eco-friendly and energy-efficient materials
Main constraints	Need changes to design methods	The complexity of tracking material flows	Focus primarily on building energy
Potential for integration	Urban mining and sustainable design	Can serve as a source of secondary materials	Forms the environmental basis of architectural design

Based on the results of the analysis conducted, urban mining is primarily concerned with extracting secondary resources from existing buildings. The concept of circular design, on the other hand, involves integrating closed material cycles directly into the design of buildings. In addition, sustainable architecture is concerned with reducing the impact of buildings on the environment by implementing energy-efficient measures.

Based on the findings of this study, it is proposed that region-oriented architectural design be viewed as an integrative approach that combines spatial analysis of building resources with the principles of circular design.

This study proposes a system of interrelationships between urban mining potential, design principles, and design tools. It is used to translate spatial-resource analysis results into architectural design solutions. In Table 2, each principle is accompanied by assessment indicators that provide a quantitative assessment of how well circular strategies are implemented during the architectural design process.

Table 2. Integration of urban mining principles into region-oriented architectural design

Potential of urban mining	Architectural principle	Design tool	Evaluation indicator
Presence of existing load-bearing structures	Adaptive reuse of buildings	The design solution adapts to the standard dimensions of elements and structural characteristics Retention of the framework. Repurposing of industrial buildings, functional transformation	IO 1 Proportion of building volume retained (%)
Reuse of structural elements	Design based on available structural resources	Use of existing frames, spans, and column grids. Changes the logic of form-making: from 'form-material' to 'resource-architectural system'	IO 2 Percentage of reused structures (%)
Availability of modular industrial structures	Modularity of architectural solutions	Modular design, transformable spaces, flexible spatial configuration, standard structural steps	IO 3 Structural modularity coefficient
Possibility of dismantling structures	Dismantlability and reversibility of connections	Dismantling, reassembly. Bolted connections, dry assembly systems.	IO 4 Proportion of structures suitable for dismantling (%)
Availability of secondary building materials	Circularity of the material cycle	Use of recycled materials (bricks, metal, panels)	IO 5 Proportion of recycled materials (%)
Geographical concentration of industrial facilities	Locality of resource flows	Use of materials from regional sources Spatial connectivity of resource flows	IO 6 Average distance of material transport
Availability of large industrial sites	Renovation of the industrial landscape	Adaptable planning structures. Comprehensive redevelopment of the area.	IO 7 Functional flexibility coefficient
Potential for future dismantling	Design for demountability.	Designing with future dismantling in mind, reversible connections.	IO 8 Proportion of materials suitable for reuse (%)

A typological analysis of 16 unused industrial buildings in Ust-Kamenogorsk identified seven types of buildings and structural configurations, making it possible to assess

their potential for integration into circular architectural design strategies. The correspondence between typologies and possible architectural applications is presented in Table 3.

Table 3. – The relationship between the typologies of the industrial building stock in Ust-Kamenogorsk and circular architectural strategies.

Typology of industrial building stock		Circular design strategy	Application in architecture
RC frame industrial buildings	Long-span structures (12 m, 18 m, 24 m)	Structural reuse/ Spatial transformation with retained frame	Public buildings and multifunctional public spaces
	Buildings with regular structural grid (3x3 m; 6x6 m)		
Steel-framed industrial buildings	Long-span structures	Demolition and reuse of structural elements/ Spatial transformation with preservation of the structural frame	Modular pavilions/ temporary public structures
	Buildings with regular structural grid		
Large-panel reinforced concrete industrial buildings	Cellular structure	Reuse of construction elements	Low-rise public buildings, administrative facilities and office buildings, residential buildings
Framed-wall industrial and warehouse buildings	Structures with a regular load-bearing grid	Adaptive spatial transformation of buildings with frame preservation	Low-rise public and residential buildings, administrative facilities
Brick industrial and warehouse buildings	Structural system with longitudinal load-bearing walls	Deconstruction and reuse of structural elements/ Adaptive reuse	Office spaces, educational campuses, administrative facilities, residential buildings

Interactions defined above include: identify structural modules and elements of industrial buildings suitable for reuse; transform them into architectural design solutions; demonstrate the possibility of creating innovative spaces based on industrial structural systems.

To illustrate the application of the proposed model, a site in Ust-Kamenogorsk, situated in the coastal zone of the Irtysh River, is examined. The industrial building built in 1956 and situated in the central part of the city, has been successively adapted for various functions (furniture production, warehouse, sales area, fitness center), reflecting its typological flexibility. The building's spatial and layout parameters, along with its structural scheme—a partial frame with two rows of brick columns supported by load-bearing exterior walls—allow the structure to be interpreted as a carrier of sustainable

spatial and structural resources within the framework of urban mining. Visually, at the level of the overall model, the stages of project development are shown in Fig. 5.

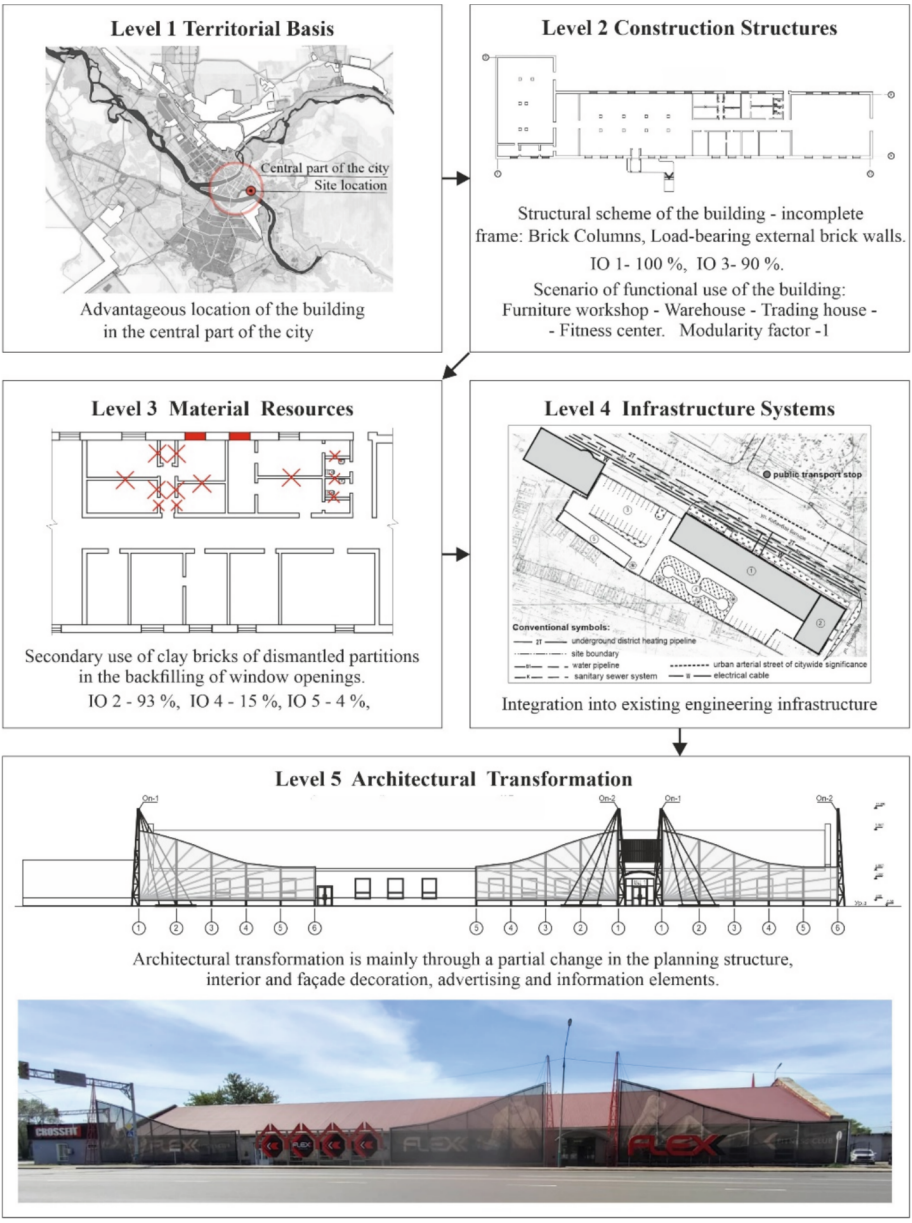

Fig. 5. Testing the model using an industrial building in Ust-Kamenogorsk as an example

Current seismic zoning requirements for the city (7 on the Richter scale) have necessitated the reinforcement of load-bearing elements with steel frames and beams. The change in the building's function and its reintegration into the urban fabric contribute to the enhancement of the waterfront area and ensure the transformation of the former industrial site into a more vibrant and community-oriented element of the urban environment. By extending the traditional understanding of urban mining and contributing to the implementation of circular economy principles, the study confirms that the industrial building stock can be regarded as a spatial-structural resource for architectural design.

In the construction industry, the challenges of the circular economy are not only technological, but also political, economic, organizational, managerial, technical, and environmental. It should be noted that the transition to circular architecture requires the transformation of the entire sector, rather than the transformation of individual technologies [18, 29]. A key characteristic of circular architecture is adaptive reuse, which significantly reduces the impact on the environment, creates new cultural values, and preserves buildings' industrial identity [30]. The post-industrial heritage can be used as a resource for sustainable development.

Taking into account the specific characteristics of post-Soviet cities, regional strengths, obstacles, and limitations, as well as opportunities for applying urban mining in Ust-Kamenogorsk, were identified (Table 4).

The advanced state of disrepair of many buildings makes mechanical demolition the predominant practice, which significantly limits the potential for urban mining. However, the city has a sufficient stock of industrial buildings constructed in more recent years that can be adapted for new uses while retaining their original volume.

5 Results

As a result of the study, a conceptual framework for region-oriented architectural design of industrial areas, based on urban mining, has been developed.

The data obtained show that the existing industrial building stock constitutes a multi-level system of spatial and material resources, comprising territorial, structural, infrastructural and material components. These elements can be interpreted as secondary structural systems capable of enabling the creation of new architectural functions without completely dismantling the original structure.

In order to facilitate the transition from material stock assessment to design solutions, a multi-scalar model of circular architectural renovation has been developed. The model operates across several spatial levels – from the urban area to the individual buildings – and comprises three sequential stages: identifying resource clusters within the industrial landscape; transforming identified resources into architectural design principles; and implementing solutions at the level of a specific building.

The greatest potential for circular renovation lies in the preservation of existing structural systems. Typical industrial architecture features include reinforced concrete and steel frames, long spans, and regular column grids. Through the preservation of these elements, it is possible to significantly reduce the consumption of primary resources, minimize the volume of construction waste, as well as guarantee flexibility in the functional renovation of buildings.

Table 4. SWOT analysis of the implementation of urban mining in Ust-Kamenogorsk.

(S) Strengths	**(W) Weaknesses (limitations)**
High concentration of industrial facilities suitable for adaptation and modernization.	Low selectivity of dismantling. Predominantly old, standardized design solutions that do not take future dismantling into account.
Large stock of obsolete Soviet-era buildings (source of secondary materials)	Lack of infrastructure for processing construction waste.
Availability of a metallurgical base and recycling facilities	Lack of a regulatory framework and standards for urban mining
High density of utility networks (potential for resource extraction)	Lack of markets for secondary materials
Availability of scientific and educational potential (school of architecture)	Lack of expertise among designers and contractors
Opportunity for integration into environmental regeneration programmer	Lack of digitalization of the building stock (no BIM passports)
(O) Opportunities	**(T) Threats**
Transition to a circular economy at national level	Economic instability and dependence on the raw materials sector
Reduced pressure on landfill sites	Low demand for recycled materials
Creation of new jobs in the 'green' economy	Risk of pollution if dismantling is carried out incorrectly
Reducing the carbon footprint of construction	Complexity of certifying recycled materials
Improving the sustainability of the urban environment	Negative public perception of 'recycled materials'

An integrated system is proposed for integrating urban mining potential into architectural design. The system establishes a relationship between the characteristics of the building stock, architectural principles, design tools, and quantitative assessments. Circular strategies may be incorporated as early as the design stage instead of only at the demolition or recycling stage.

A spatial analysis of Ust-Kamenogorsk identified industrial sites with potential for adaptive reuse. Using the example of the renovation of one such facility, this paper demonstrates a strategy for implementing a multiscale model in real-world conditions. As a result of the pilot study, the typological and structural characteristics of the facility were identified, the feasibility of preserving existing spatial and structural systems while changing the building's functional purpose was confirmed, and the impact of the facility's transformation on the urban context was determined.

The SWOT analysis revealed significant resource and logistical advantages, while also identifying critical constraints, including the lack of a regulatory framework, infrastructure for processing construction waste, digital building inventories, and a developed market for recycled materials.

6 Discussion

The findings indicate the need to rethink the role of urban mining in architectural design as a methodological foundation for developing architectural solutions.

The proposed approach facilitates a transition from the linear "demolition–new construction" model to a model of adaptive regeneration of the industrial environment. In this model, existing sites and buildings serve as vessels for spatial, structural and cultural potential. This is particularly relevant to post-Soviet industrial cities that possess a significant stock of standardized structures with high load-bearing capacities.

Compared with international practices, western and European countries support circular construction through regulatory instruments, digital material registers, and secondary resource markets. Circular strategies are at an early stage of development in the region under study, which significantly limits their implementation. As well as this, post-Soviet industrial cities possess a unique combination of factors: a high concentration of material stocks, a compact urban structure, and close proximity to industrial and storage areas. The presence of these characteristics creates favorable conditions for the flow of circular resources within the local area, provided appropriate planning and management tools are in place.

It is also confirmed by the research findings that adaptive reuse is the most environmentally effective strategy for circular architecture. A significant reduction in embodied carbon, a reduction in waste volume, and preservation of the industrial identity of the area can all be achieved by retaining existing structures.

The study is limited by the lack of detailed quantitative data on the material composition of the building stock. The primary focus has been placed on typological analysis without conducting full-scale life-cycle assessments. A promising area of future research is the development of digital building registers, GIS mapping of material stocks, and quantitative models for assessing circular efficiencies.

7 Conclusions

The study confirms that industrial sites can be reimagined as spatially organized material resources for circular development. The developed multi-level model facilitates the transition from analyzing a site's resource potential to formulating specific design solutions, linking urban planning and architectural levels. There is significant potential for functional renovation of industrial buildings from the Soviet era that does not require a significant investment of resources.

Testing of the model confirmed its suitability for analyzing the transformation of industrial sites, preserving their spatial and structural systems, reusing materials, and assessing the impact on the urban context.

In industrial regions, circular strategies are constrained by institutional, economic, and technological barriers. In order to achieve this, it is necessary to develop a specialised regulatory framework as well as tools for managing digital resources.

Thus, the integration of urban mining principles into region-oriented architectural design opens up prospects for the sustainable renewal of industrial cities.

It is imperative that further research be conducted in the following areas to ensure the practical implementation of the strategy in the region:

- develop a classification of enterprises into groups, taking into account technological processes and environmental impact, to determine the extent of potential renovation of industrial sites or their demolition;
- to study the typology of industrial buildings based on structural and spatial characteristics, taking into account the differences in the life cycle of its main elements, which determine the possibilities and scenarios for regeneration;
- to identify standardized and unified structural systems and their components used in the region under study and to determine the future nature of their use (within the structure of the preserved facility, partial or complete replacement, or the reprocessing of replaceable components);
- to develop methodological recommendations on the application of circular economy principles in the architectural design of the industrial cluster in the East Kazakhstan Region.
- This study contributes to the development of the circular economy in the region, in accordance with the institutional documents of the Republic of Kazakhstan.

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Disclosure of Interests The authors declare no competing interests.

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