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STUDY ON EVALUATION OF PROTECTION, UTILIZATION AND DEVELOPMENT OF TRADITIONAL VILLAGES BASED ON IMPROVED FUZZY COMPREHENSIVE EVALUATION – A CASE STUDY OF YOUYANG COUNTY, CHONGQING

With the rapid acceleration of urbanization, traditional villages in China face increasing pressures of preservation and development. As vital carriers of ethnic culture and ecological value, these settlements require a scientific framework to assess their protection, utilization, and development levels. This study focuses on Youyang County in Chongqing, an area rich in ethnic culture and diverse ecological environments, to construct a comprehensive evaluation system based on an **improved fuzzy comprehensive evaluation method**. By integrating multi-dimensional indicators—cultural value, ecological environment, economic development, and social participation—the proposed model addresses limitations in weight determination and membership degree calculation inherent in traditional fuzzy methods. Empirical analysis verifies the method's effectiveness and stability, revealing that Youyang's traditional villages excel in cultural preservation and ecological quality but lag in economic vitality and community engagement. The paper proposes targeted strategies for sustainable protection and utilization, aiming to balance cultural inheritance with rural revitalization. This research contributes both theoretical insights and practical guidance for enhancing traditional village management, offering a replicable framework for other regions seeking to harmonize cultural heritage protection and sustainable rural development.

Keywords: Traditional villages; Fuzzy comprehensive evaluation; Youyang County; Cultural heritage; Sustainable development; Rural revitalization.

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1. RESEARCH BACKGROUND AND SLECTION BASIS

1.1. Particularity and Practical Needs of Protection and Utilization of Traditional Villages in Youyang County

As an important cultural node in the Wuling Mountain area, Youyang Tujia and Miao Autonomous County of Chongqing is rich in unique traditional village resources. By 2023, a total of 41 villages in the county have been included in the list of Chinese Traditional Villages, ranking among the top in Chongqing. These villages not only preserve intact Tujia and Miao stilted building complexes and rich intangible cultural heritage, but also carry unique mountain agricultural civilization and memories of ethnic cultural exchanges.

However, traditional villages in Youyang County also face multiple contradictions between protection and development: the "hollowing" problem brought by rapid urbanization, conflicts between tourism development and authenticity protection, tensions between modern lifestyles and traditional style maintenance, etc. It is urgent to find a balance through scientific evaluation and systematic research. In addition, the "14th Five-Year Plan for Rural Construction in Chongqing" clearly puts forward the requirement of "inheriting excellent ethnic minority cultures and promoting the activated utilization of traditional villages". As the core area for the protection of traditional villages in southeastern Chongqing, Youyang County needs a targeted evaluation tool that can not only identify the "protection shortcomings" of different villages, but also measure the "utilization benefits", so as to provide data support for differentiated protection strategies.

Youyang County is located in the hinterland of the Wuling Mountains, with more mountains and fewer plains. Traditional villages are mostly distributed along river valleys and slopes, forming a spatial form of "leaning against mountains and near water, with stilted buildings standing in the air". This symbiotic pattern of "mountains-architecture-culture" requires the protection evaluation to additionally focus on "ecological adaptability" and "spatial integrity". At the same time, Tujia people account for more than 40% of the population in Youyang County. In traditional villages, "construction rituals, living customs and intangible culture" are deeply bound to the architectural space. This coupling of "material space and intangible culture" requires the evaluation system to break through the limitation of "only focusing on the building itself" and include indicators such as "degree of cultural inheritance" and "degree of community participation" [1].

As a key assistance county for rural revitalization in Chongqing, traditional villages in Youyang County are in a critical period of "initial protection, exploration of utilization and development transformation". Some villages have initially realized the integration of "traditional villages + agricultural tourism", some are still in the original protection state, and others are to be developed, so it is urgent to clarify the development direction.

1.2. Existing Shortcomings and Improvement Needs of Traditional Village Evaluation Systems

A scientific evaluation system is the core tool to solve the contradictions between protection and development, but current research and practice still have significant defects. Early evaluations mostly focused on the integrity of material space and the survival of intangible cultural heritage. Although the dimension of "interaction between culture and people" was added after 2022, they still mainly rely on qualitative descriptions, lacking quantitative integration of "material-culture-ecology-economy" multiple dimensions.

In existing quantitative studies, the fuzzy comprehensive evaluation method is widely used because it is good at dealing with fuzzy indicators such as "building damage degree" and "cultural vitality", but its traditional model has key limitations—strong subjectivity in weight determination. Relying solely on expert scoring is prone to value imbalance affected by the evaluator's professional background, which is seriously disconnected from the protection needs of Youyang's composite heritage, making it difficult to accurately identify the short-board links in "building protection-industrial development-ecological maintenance".

With the advancement of concentrated contiguous protection policies, Youyang County urgently needs a quantitative tool that balances professional judgment and objective data. The core improvement direction of this study is to introduce a subjective-objective combined weighting model of "Analytic Hierarchy Process (AHP) + entropy weight method". AHP can integrate the experience judgments of experts in multiple fields to ensure the professional weight of core architectural indicators; the entropy weight method can objectively correct weight deviations through information entropy calculation based on the field survey data of 41 villages in Youyang, avoiding evaluation imbalance caused by subjective assumptions [2].This combined model has been verified for scientificity in similar studies, and its application can accurately quantify the protection and utilization level of villages in Youyang County, providing data support for resource allocation and policy optimization.

1.3. Practical Significance of the Research

Current research on traditional villages mostly focuses on the single dimension of "protection status", and evaluation tools generally have the defect of "emphasizing protection, neglecting utilization and weakening development", leading to contradictions such as "buildings are protected but villagers have difficulty increasing income" and "intangible cultural heritage is inherited but transformation efficiency is low" in demonstration counties such as Youyang. For example, although Hejiayan Village in Youyang has completed 85% of terrace ecological protection, due to the failure to include "degree of integration of culture and tourism" in the evaluation, the annual revenue of intangible cultural heritage workshops only accounts for 12%

of the village collective income, and the disconnection between protection, utilization and development is prominent [3].

The core breakthrough of the "quantitative tool integrating the improved fuzzy comprehensive evaluation method" constructed in this study is to incorporate the three-dimensional goals of "protection, utilization and development" into a unified evaluation framework. The index system includes not only protection indicators, but also utilization indicators and additional development indicators; at the same time, through the combined weighting of AHP + entropy weight method, it not only relies on expert experience to ensure the professional logic of "protection first", but also corrects weights through field data, so that indicators such as "utilization efficiency" and "development potential" obtain reasonable weight allocation, completely changing the limitation of "single dimension and fragmented goals" of traditional evaluations, and providing quantitative support for the coordinated advancement of "protection-utilization-development". Therefore, the construction of this quantitative tool can provide decision-making basis for the protection of traditional villages in Youyang County and even the whole country, and assist in the implementation of the rural revitalization strategy.

2. DOMESTIC AND FOREIGN RESEARCH STATUS AND DEVELOPMENT

2.1. TResearch Review and Theoretical Framework Construction

2.1.1. Deficiencies of Existing Research and Improvement Directions

Although existing research has achieved certain results in the evaluation of the protection, utilization and development level of traditional villages, there are still several deficiencies. Most evaluation index systems focus on a single dimension, lacking comprehensive consideration of culture, ecology, economy, society and other multiple dimensions, leading to one-sided evaluation results. The traditional fuzzy comprehensive evaluation method has problems of strong subjectivity and insufficient stability in weight determination and membership degree calculation, affecting the scientificity and accuracy of evaluation. Most existing research focuses on static evaluation, lacking tracking analysis of the dynamic change process of traditional villages [4].

In response to the above deficiencies, the improvement directions should include: constructing a multi-dimensional and hierarchical evaluation index system; introducing improved weight determination methods, such as the combination of Analytic Hierarchy Process (AHP) and entropy weight method, to improve the objectivity of weights; optimizing membership function to enhance the robustness of the model; and combining time series data to realize

dynamic evaluation and prediction, improving the practical value and guiding significance of evaluation.

2.2.3. Design Idea of the Theoretical Framework of This Study

The design idea of the theoretical framework of this study is based on the concept of multi-dimensional comprehensive evaluation, combining the complexity of the protection, utilization and development of traditional villages to construct a systematic index system. Four dimensions including cultural value, ecological environment, economic development and social participation are selected as the core of evaluation to ensure the comprehensiveness and representativeness of evaluation content. The improved fuzzy comprehensive evaluation method is adopted to model the fuzzy membership relationship of each index by determining the weight vector and membership matrix. Fuzzy comprehensive operation is used to obtain the comprehensive evaluation result, improving the scientificity and stability of evaluation. This framework not only inherits the advantages of traditional fuzzy evaluation, but also optimizes the weight determination, adapting to the actual needs of the protection and utilization of traditional villages [5].

3. MAIN RESEARCH CONTENT

3.1. Construction of the Index System for the Protection, Utilization and Development of Traditional Villages

The construction of the index system for the protection, utilization and development level of traditional villages is the core link of the evaluation research. Based on literature review and field survey, indicators covering four dimensions of cultural value, ecological environment, economic development and social participation are selected. Cultural value indicators include the degree of protection of historical relics and the status of intangible cultural heritage inheritance; ecological environment indicators cover the integrity of natural landscape and environmental quality; economic development indicators focus on the village economic structure and tourism income; social participation indicators reflect the enthusiasm of residents in participating in protection and development.

3.2. Design and Application of the Improved Fuzzy Comprehensive Evaluation Model

Aiming at the deficiencies of the traditional fuzzy comprehensive evaluation model in weight determination and membership degree calculation, this paper proposes an improved method. By introducing the weight determination mechanism

combining the Analytic Hierarchy Process (AHP) and entropy weight method, it not only considers expert subjective judgment, but also takes into account the objective variability of data, improving the scientificity of weight allocation.

In the design of membership function, an improved triangular fuzzy membership function is adopted to enhance the ability to express the fuzziness of evaluation indicators. This model shows high stability and accuracy in the evaluation of the protection, utilization and development level of traditional villages in Youyang County [6].

3.3. Empirical Analysis Taking Youyang County as an Example

This study takes the traditional villages in Youyang County, Chongqing as the empirical object. Based on the constructed evaluation index system, the improved fuzzy comprehensive evaluation model is used to systematically analyze their protection, utilization and development levels. Relevant data are collected through questionnaires and field surveys to determine the membership function and weight vector of each indicator. The improved fuzzy comprehensive evaluation formula (where A is the weight vector and R is the membership matrix) is used to calculate the comprehensive evaluation result.

According to the evaluation results, a multi-dimensional analysis is carried out on the cultural protection, ecological environment, economic development and social participation of traditional villages in Youyang County, their advantages and deficiencies are identified, and targeted protection and development strategies are proposed to provide scientific basis for the sustainable development of traditional villages.

4. IMPLEMENTATION PLAN

4.1. Phase 1: Preparation and Design (Early Stage of Research)

Clarify the research object: Among the 59 Chinese Traditional Villages announced by Youyang County, 3-5 representative villages are selected as core evaluation units according to their cultural types (such as Tujia and Miao characteristics), spatial forms (such as river valleys and mountains), and development status (such as tourism development type and original protection type).

Construct a preliminary evaluation index system: Based on literature review and understanding of the trinity goals of “protection-utilization-development” of traditional villages, a three-level evaluation index system including target layer, criterion layer and indicator layer is initially constructed. The target layer is the comprehensive evaluation of the protection, utilization and development of traditional villages; the criterion layer is carried out from three dimensions: “heritage value

protection (B1)", "activated utilization level (B2)" and "sustainable development capacity (B3)"; the indicator layer sets specific and measurable indicators under each criterion [7].

Indicator screening and determination: Through expert consultation (Delphi method), the preliminary indicator system is screened, supplemented and revised, and indicators with strong correlation or difficult data acquisition are eliminated, and finally a formal evaluation index system in line with the regional characteristics of Youyang County is formed.

4.2. Phase 2: Data Collection and Processing

Multi-source data collection: For the determined indicator system, multi-channel data collection work is carried out. Field survey data: Design questionnaires and interview outlines for qualitative or semi-quantitative indicators such as "integrity of historical buildings" and "villagers' satisfaction", and conduct in-depth village data collection; government statistical data: Obtain social and economic data such as population, economy and tourism income from official channels such as the "Youyang County Statistical Yearbook", local government work reports, and cultural and tourism development departments [8];

GIS spatial data: Purchase or download high-resolution satellite images, Digital Elevation Model (DEM), land use status maps, etc. of Youyang County, and use UAVs for oblique photography of core areas to establish 3D models. Conduct spatial quantitative analysis of village building density, road network, public service facility distribution, etc. through the GIS platform.

4.3. Phase 3: Model Evaluation and Analysis

Determine the comprehensive weight: Calculate the subjective weight (AHP), invite experts to conduct pairwise comparisons of the importance of indicators at all levels, construct a judgment matrix, calculate the weight and pass the consistency test; calculate the objective weight (entropy weight method), use the standardized quantitative indicator data to obtain the objective weight of each indicator according to the calculation steps of the entropy weight method; the combined weight is calculated using the formula to obtain the final comprehensive weight.

Determine the set of evaluation criteria and set the evaluation levels. Define the membership functions accordingly: for quantitative indicators, use appropriate membership functions (such as trapezoidal distribution or Gaussian distribution) to calculate their membership levels for each evaluation category; for qualitative indicators, determine their membership levels based on the scores given by experts or the results of questionnaire surveys. Finally, construct a single-factor evaluation matrix by combining the membership vectors of all indicators to form a fuzzy relationship matrix [9].

By applying the fuzzy synthesis operator, the comprehensive weight vector is combined with the fuzzy relationship matrix to obtain the final comprehensive evaluation result vector. Based on the principle of maximum membership degree, the final evaluation grade for each village is determined. Additionally, the scores obtained by each village in the three criteria areas of "protection," "utilization," and "development" are analyzed in order to identify its strengths and weaknesses.

4.4. Phase 4: Conclusions and Countermeasures

Result analysis and visualization: Combine GIS to spatially visualize the evaluation results, generate an evaluation thematic map of the protection, utilization and development level of traditional villages in Youyang County, and intuitively show the comprehensive level and spatial differentiation characteristics of each village.

Put forward countermeasures and suggestions: Based on the evaluation results, put forward refined and differentiated protection, utilization and development strategies for villages of different types and development levels. For example, for villages with good protection but insufficient utilization, propose activation paths; for over-commercialized villages, put forward suggestions for cultural return and community empowerment [10].

5. EXPECTED GOALS

5.1. Main Achievements

Based on the improved fuzzy comprehensive evaluation method, this study systematically evaluates the protection, utilization and development level of traditional villages in Youyang County, Chongqing, and is expected to achieve important achievements in the following aspects.

By constructing a scientific and reasonable evaluation index system, it can comprehensively reflect the current situation and potential of traditional villages in multiple dimensions such as cultural inheritance, ecological environment, economic development and social management, providing data support and theoretical basis for relevant decisions.

The improved fuzzy comprehensive evaluation method shows higher accuracy and adaptability in dealing with complex, variable and fuzzy information of traditional villages, helping to overcome the shortcomings of strong subjectivity and unreasonable weight allocation in traditional evaluation methods, and improving the objectivity and scientificity of evaluation results.

The research results will provide operable strategic suggestions for the protection and utilization of traditional villages in Youyang County and similar areas,

promote the effective protection and rational development of cultural heritage, and realize the win-win of economic benefits and ecological benefits.

5.2. Theoretical Significance

This study has innovations in both theory and method, enriches the evaluation tool library in the field of traditional village protection, and promotes the application and expansion of the fuzzy comprehensive evaluation method in cultural heritage protection. The constructed three-dimensional evaluation framework of "protection-utilization-development" breaks through the limitation of the single dimension of traditional evaluation, providing a new idea for the improvement of the traditional village evaluation system. The application of the AHP-entropy weight method combined weighting model provides an effective solution to the problem of strong subjectivity in weight determination in fuzzy comprehensive evaluation, improving the scientificity and reliability of the evaluation model.

5.3. Practical Application Value

The research results help to improve the public and government's understanding of the value of traditional villages, enhance protection awareness, and promote the participation of all sectors of society in the sustainable development of traditional villages. It provides data support for the formulation of differentiated protection strategies for traditional villages in Youyang County, effectively solves the problem of disconnection between protection and development locally, and assists in the implementation of the rural revitalization strategy. The evaluation method and index system formed by the research have strong promotion, which can provide reference for the evaluation of the protection and utilization of traditional villages in other areas, and promote the overall improvement of the protection and utilization level of traditional villages in the country.

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BADANIE OCENY OCHRONY, WYKORZYSTANIA I ROZWOJU TRADYCYJNYCH WIOSEK W OPARCIU O ULEPSZONĄ KOMPLEKSOWĄ OCENĘ ROZMYTĄ – STUDIUM PRZYPADKU POWIATU YOUYANG W CHONGQING

Streszczenie

Wraz z gwałtownym przyspieszeniem urbanizacji, tradycyjne wioski w Chinach stoją w obliczu rosnącej presji związanej z zachowaniem i przekształcaniem zasobów. Jako istotne nośniki wartości kulturowej i ekologicznej, osady te wymagają naukowych ram do oceny ich ochrony, użytkowania i właściwego rozwoju. Niniejsze badanie koncentruje się na powiecie Youyang w Chongqing, regionie bogatym w rodzime walory kultury i zróżnicowanym środowisku ekologicznym, aby zbudować kompleksowy system ewaluacji oparty na ulepszonej, kompleksowej metodzie ewaluacji rozmytej. Poprzez integrację

wielowymiarowych wskaźników – wartości kulturowej, środowiska ekologicznego, rozwoju gospodarczego i uczestnictwa społecznego – proponowany model uwzględnia ograniczenia w określaniu wagi i obliczaniu stopnia przynależności, nieodłącznie związane z tradycyjnymi metodami rozmytymi. Analiza empiryczna weryfikuje skuteczność i stabilność tej metody, wykazując, że tradycyjne wioski Youyang przodują pod względem zachowania kultury i jakości ekologicznej, ale pozostają w tyle pod względem witalności gospodarczej i zaangażowania społeczności. W artykule zaproponowano ukierunkowane strategie zrównoważonej ochrony i użytkowania mające na celu zrównoważenie dziedzictwa kulturowego z rewitalizacją obszarów wiejskich. Badania te dostarczają zarówno teoretycznych obserwacji, jak i praktycznych wskazówek dotyczących doskonalenia tradycyjnego zarządzania wsią, oferując powtarzalne ramy dla innych regionów dążących do harmonizacji ochrony dziedzictwa kulturowego ze zrównoważonym rozwojem obszarów wiejskich.

Słowa kluczowe: Tradycyjne wioski; Kompleksowa ocena rozmyta; Powiat Youyang; Dziedzictwo kulturowe; Zrównoważony rozwój; Rewitalizacja obszarów wiejskich.

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IMPLEMENTING THE BLUE-GREEN INFRASTRUCTURE APPROACH IN LANDSCAPE ARCHITECTURE

The Blue – Green Infrastructure (BGI) represents an innovative and integrative approach in **landscape architecture**, combining water and vegetation systems to create a more firmly established, resilient, and multi – functional urban environment. This study explores the role of BGI in promoting **sustainable development**, emphasizing its capacity to manage stormwater, enhance **biodiversity**, and improve urban microclimates.

Through architecture design interventions such as green roofs, rain gardens, vertical greening systems, and permeable pavements, BGI transforms conventional grey infrastructure into dynamic ecological networks that support environmental and **social benefits**.

By introducing a few case studies from urban contexts and urban campuses, the findings highlight the significance of integrating ecological processes and social values into landscape architecture design, reinforcing BGI as a cornerstone of sustainable and livable urban futures.

Implementing the Blue – Green Infrastructure approach creates more inclusive cities by integrating people with nature as well as facilitating climate adaptation.

Keywords: Blue-green infrastructures (BGI) Landscape architecture; Sustainable development; Social benefits;Biodiversity

1. RESEARCH BACKGROUND

The In landscape architecture,Blue-green infrastructures(BGI)is not simply an engineering solution for stormwater management—it is a **design philosophy**. It integrates water as a visible, dynamic, and expressive element, and vegetation as a functional infrastructure that supports life and well-being. The blue-green palette becomes both a technical strategy and a poetic language of urban form.

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Blue-green infrastructures (BGI) integrate solutions implemented to enhance water management and landscape values for more climate resilient and livable cities. BGI have created an opportunity to renew the natural structure of water balance in cities through the increase in rainwater retention and enlargement of permeable areas.[1]

Blue-Green Infrastructure (BGI) incorporates natural and semi-natural systems designed to alleviate the impacts of climate change, notably urban heat, in city environments[2]. Green infrastructure refers to an interconnected network of green spaces, consisting of various open spaces and natural areas, including parks, green belts, green roofs, and green facades, all covered with vegetation. It regulates surface energy processes through mechanisms like evaporation, shadowing, and adjusting emissivity[3]

Introducing blue–green infrastructure to cities offers benefits in water retention, micro-climate regulation, and biodiversity enhancement. In cities with a rich history of historical watercourses, these features can be an incentive for activities involving the discovery, restoration, and exposure of cultural heritage. The discussed examples from Poznan, Milan, and Beijing show that the restoration of historical watercourses in cities is possible under certain circumstances[4].

Both Green Infrastructure, widely regarded as a primary strategy for mitigating urban heat environments, and Blue Infrastructure play significant roles in influencing the spatial distribution of surface temperatures. Jung et al. (2021) found that the canopy area of trees is negatively correlated with surface temperature, with the mitigating effect varying based on the degree of urbanization and current canopy coverage[5].

The term “infrastructure” in BGI indicates that the role of natural processes involving vegetation or water features is essential in providing a variety of ser-vices to urban residents. The GI and BI in BGI are a significant enhancement of the GI idea. It should be noted that the proper functioning of plant elements depends on water resources. Simultaneously, vegetation determines the activity of local hydrological processes[6]**.**

Against the backdrop of accelerated urbanization, traditional hard infrastructure such as drainage systems and sewage treatment plants cannot effectively solve many environmental problems, especially water pollution, air quality decline and biodiversity loss.

Green infrastructure makes up for this deficiency by restoring and utilizing natural systems and playing an ecological role. Its main application areas include urban rainwater management, ecological restoration, green building and wetland restoration. For example, rain gardens, green roofs and permeable paving technologies have been widely used in urban rainwater management to absorb rainwater, reduce flood risk and improve water quality, and optimize the structure of urban ecosystems.

At the same time, ecological restoration methods such as wetland restoration and vegetation cover have also been applied in many areas. These methods restore soil and water conservation functions and biological habitats through natural ecological

processes and enhance the environmental adaptability of cities. In the field of green building, more and more new buildings are beginning to adopt green infrastructure such as green roofs and green walls, which not only improve the microclimate of buildings, but also effectively reduce energy consumption.

The construction of green space systems such as urban parks and greenspace has also become an important part of urban ecosystem construction, and green infrastructure plays an indispensable role in this regard. Taking some large cities in China as examples, many cities have improved the ecological function of public spaces, mitigated the urban heat island effect, and improved the quality of life for citizens by implementing green infrastructure construction. However, the widespread application of green infrastructure still faces challenges such as insufficient funding, incomplete technical standards, and inadequate policy support. These constraints have, to some extent, affected its effectiveness. Further improving the technological maturity of green infrastructure, perfecting the relevant policy system, and strengthening cooperation among all sectors of society are key to promoting its in-depth development.

2. THE DESIGN FRAMEWORK OF BLUE-GREEN INFRASTRUCTURE

The **Blue-Green Infrastructure (BGI) Design Framework** integrates water and vegetation systems to create resilient, multifunctional, and connected urban environments. It combines **blue systems** (wetlands, rain gardens), **green systems** (parks, green roofs), and **hybrid elements** (permeable pavements, green streets) to manage stormwater, enhance biodiversity, and improve urban livability.

Applied across urban, neighborhood, and site scales, BGI supports flood control, cooling, habitat creation, and social well-being. Its success depends on collaboration among planners, ecologists, and communities, supported by policies and continuous monitoring. Overall, BGI links ecological and social functions, transforming cities into sustainable, climate-adaptive, and people-centered landscapes.

As the research approach, the literatures based on WoS **Fig.1** has been collected, searching the key elements in the database we can find the most have been reported or in the case studies is coming up with green roof infrastructure and then the water element like rain garden.

Concerning four most popular BGI elements,from various BGI solutions reported in the literature, the four most popular BGI elements were selected for detailed analyses: rain gardens, green roofs, VGS, and permeable pavements. According to Versini et al. (2018), these four elements were the most important and popular due to a number of benefits for urban spaces. The description of each solution comprised a definition, types, and classification criteria. The importance of each element was presented in the relation to its role for water management[7].

Among the various solutions of BGI, the highlights would be given to four elements, which combine and design solutions used in water management systems: **rain gardens, green roofs, vertical greening systems, and permeable pavements**. Below provide their characteristics, types and features that enable effective support for water management in the cities. It should be noted that their potential results from the possibility of installation in a dispersed manner, tailored to the individual characteristics of a given area.

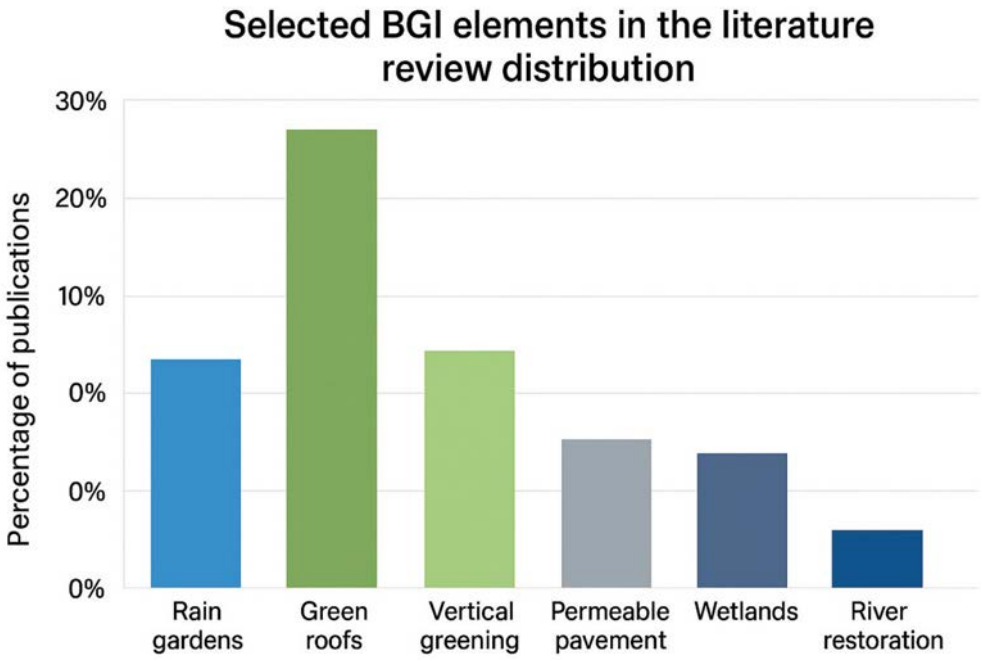

Fig. 1. The publications research distribution percentage on selected the key elements in BGI solution in Landscape Architecture application.Source :own study based on web of science core collection

3. BLUE GREEN INFRASTRUCTURE APPLICATION IN LANDSCAPE ARCHITECTURE – CASE STUDIES

3.1. Adaptation flood management and incorporating green infrastructure – smart solution BGI – case study from Germany

These large-scale urban projects highlight the importance of adapting the climate challenges while promoting ecological solutions and social well-being. HafenCity from Germany is a large-scale urban development project in Hamburg, Germany, transforming a former port area into a vibrant, mixed-use

neighborhood. By implementing green architecture, revitalizing the Elbe waterfront, and balancing residential, commercial, and cultural uses,the project aims to create a vibrant and friendly neighborhood. By integrating flexible flood protection measures that adapt to changing water levels, incorporating green roofs, green walls, and extensive parks to improve air quality, manage storm-water, and enhance urban biodiversity. combine historical preservation with contemporary architecture and sustainable urban planning. Converting an industrial port area into a residential and commercial district presented significant challenges, including environmental remediation, infrastructure development, traffic management, and preserving the area's historical character. Smart to use the Blue green infrastructure, the urban regeneration project focuses on sustainability, public space, and cultural integration by preserving historic buildings and urban context.

The Master plan as shown **Fig.2** which defines the basic elements of Hafencity developments was conceived from the outset as a flexible, updated concept, designed to be refined and firmed up over the course of the planning and development process. The basic Blue green infrastructure elements had been clarified as the **Fig.2** shown below.

Fig. 2. The masterplan of Hafencity, which defines the basic objectives of HafenCity development Source from :https://www.hafencity.com/en/overview/masterplan @KCAP/ ASTOC

3.2. BGI soultion in design a raingarden case study from Pekin University Campus

Due to the suffering from the waterlogged in the southern part of the campus of Pekin University, the campus was constructed with high intensity, which has led to severe waterlogging and runoff pollution. The lawns between the buildings are not for the social activities and has no effect to reduce surface rainwater runoff.

The rain garden project had been designed in this campus and the designer team from University Design and biuld Association of Pekin University had selected a typical green space of 300m^2 in the dormitory area as the pilot.

The most used sidewalks on both sides of the site had been retained asa well as all the high greenery had been maximally retained on the site. A small square of 5 m by 5 m is defined by the odd persimmon and walnut trees. The square divides the long and narrow green space into a larger and a smaller bioretention. Therefore some of retention ponds had been to reduce in order to provide some space for bikes parking in the campus nearby the dormitory.

In terms of c**ollection and reuse of rainwater, t**he rain garden can manage the runoff generated by the surrounding impervious surface of 572 square meters, reducing up to 16 cubic meters of rainwater for the dormitory area. (https://mooool.com/harvesting)

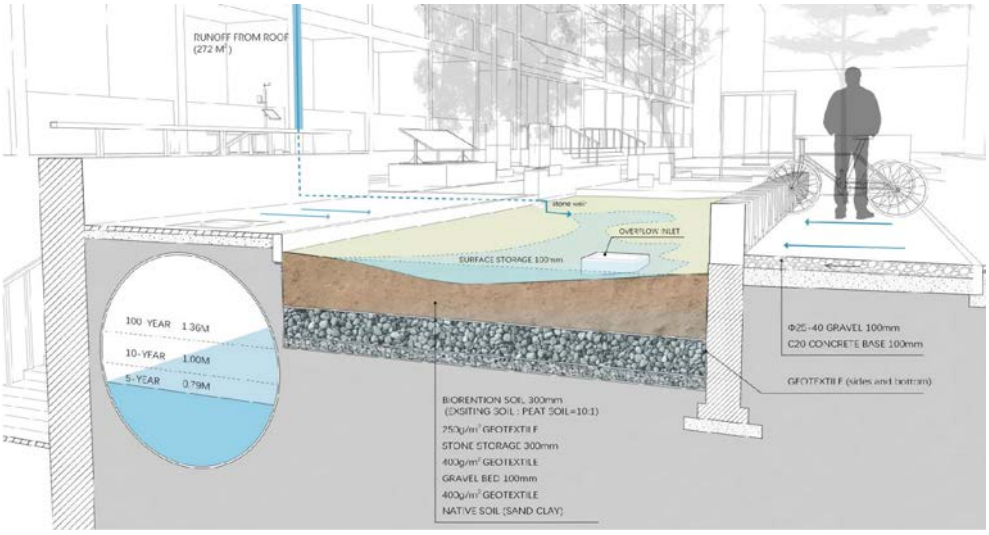

Fig.3. The rainwater garden collection in order to reduce the waterlogging problem in Pekin UNiverity Campus provided from Hao Zhang, Kangfu Zhuo, the Source from https://mooool.com/harvesting

3.3. The Blue green infrastructure solution applied in landscape Architecture design – a case study from Campus space design modeling

This project was aimed to regenerating the campus Warta and to create the future green campus and the tasks were given to students during the landscape Architectural classes as the exercises. This project was based on the sector between two high teaching buildings in the campus. The main function is adapting the green surface and maximally use the rainwater collection to enrich the limited open space ir order to provide the pace for students for social activities.

The landscape design emphasizes a balanced integration of natural elements and campus infrastructures. Maple and fir trees are used to create diverse textures, seasonal colors, and natural sound barriers. Tree-lined paths and green zones visually and functionally connect various areas of the campus, ensuring an inviting and cohesive environment. As shown in **Fig. 4 t**he project focuses on enhancing both the functionality and aesthetics of the space, with recreational zones, green corridors, and plantings designed to provide a harmonious blend of usability and nature. Sustainable measures like rainwater systems and drought-resistant vegetation further contribute to the ecological vision of the campus.

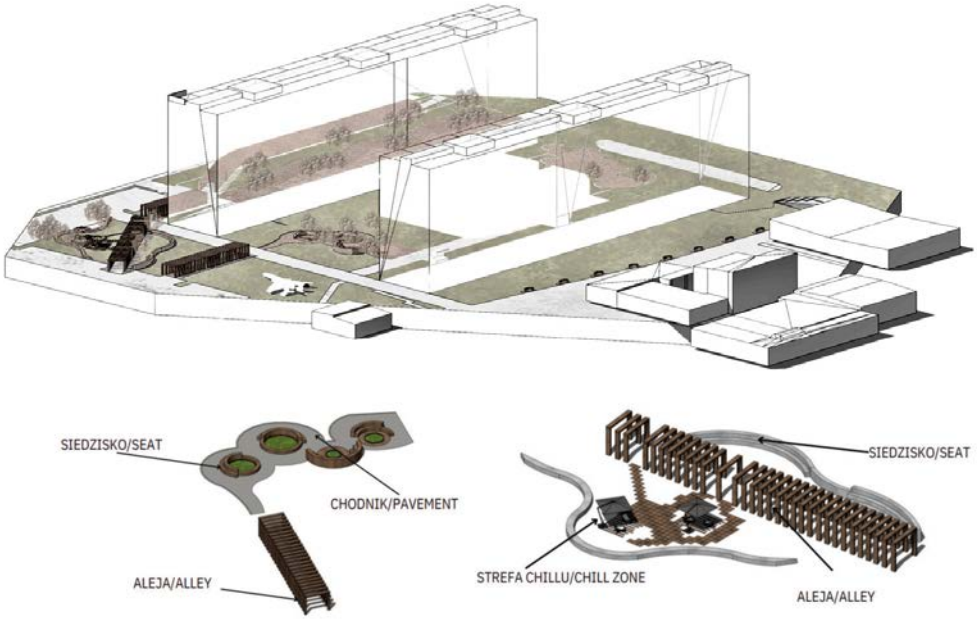

Fig. 4. The AXONOMETRY, and the concept development of a sector space between teaching buildings in Campus Warta from Poznan University of Technology. Drawn from Plewa K.,Stępniewska J., Szymanek M., Szymanowska E., Szyszka W. Supervised by Mo Zhou

4. CONCLUSIONS

The Blue-Green Infrastructure approach represents a transformative opportunity for landscape architecture to contribute to urban resilience and ecological restoration. By embedding water-sensitive design and ecosystem services into urban fabrics, landscape architects can lead the transition toward regenerative cities. Future research should focus on quantitative performance assessment, climate adaptation modeling, and community-driven design methodologies.

In terms of **biodiversity**, green infrastructure can provide habitats for plants and animals and promote ecological restoration. Measures such as wetland restoration and ecological corridor construction provide more habitats for urban ecosystems, enhance the connectivity of ecosystems, and thus promote the diversity and stability of biological populations. Through these measures, not only has the local ecological environment been improved, but urban residents have also been provided with more opportunities to get close to nature, and people's ecological awareness and environmental protection actions have been enhanced.

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WDRAŻANIE PODEJŚCIA NIEBIESKO-ZIELONEJ INFRASTRUKTURY W ARCHITEKTURZE KRAJOBRAZU

Streszczenie

Koncept błękitno-zielonej infrastruktury (BZI) prezentuje innowacyjne i zintegrowane podejście w architekturze krajobrazu, łącząc funkcjonowanie systemów wodnych i roślinnych w celu stworzenia trwalszego, bardziej odpornego i wielofunkcyjnego środowiska miejskiego. Niniejsze badanie analizuje rolę BZI w zapewnianiu zrównoważonego rozwoju,

podkreślając możliwość zarządzania wodami opadowymi i zwiększania bioróżnorodności oraz poprawy mikroklimatu miejskiego.

Poprzez interwencje architektoniczne, takie jak zielone dachy, ogrody deszczowe, pionowe systemy zieleni i przepuszczalne nawierzchnie, w dynamiczne sieci ekologiczne, które wspierają korzyści środowiskowe i społeczne.

Przedstawiając wybrane studia przypadków przestrzeni miejskich i kampusów, przedstawione wyniki podkreślają znaczenie integracji procesów ekologicznych i wartości społecznych w projektowaniu architektury krajobrazu, postrzegając koncepcję BZI jako fundamentu wspierającego zrównoważoną i przyjazną mieszkańcom przyszłość miast.BZI przekształca konwencjonalną szarą infrastrukturę. Projekt ramowy infrastruktury niebiesko-zielonej (BGI) integruje systemy wodne i roślinne w celu tworzenia wielofunkcyjnych, odpornych i połączonych środowisk miejskich.

Wdrożenie konceptu błękitno-zielonej infrastruktury pomaga tworzyć bardziej inkluzywne miasta poprzez integrację ludzi z naturą, a także wspierąć adaptację do zmian klimatu.

Słowa kluczowe: błękitno-zielona infrastruktura(BZI), Architektura krajobrazu, Rozwój zrównoważony, Korzyści społeczne, Różnorodność biologiczna

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DESIGN AS A CATALYST OF URBAN TRANSFORMATION: THE HIGH LINE IN NEW YORK, ITS GLOBAL REINTERPRETATIONS, AND IMPLICATIONS FOR POLISH PLANNING PRACTICE

This paper explores design as a catalyst of urban transformation and as an epistemic instrument within contemporary planning culture. Using New York's High Line and its global reinterpretations − including The Bentway in Toronto, Cheonggyecheon in Seoul, Nordhavn in Copenhagen, and King's Cross in London − the study traces a paradigmatic shift from design as aestheticization to design as mediation and co-production. These cases demonstrate how urban design operates not only through form-making but through iterative processes of governance, observation, learning, and negotiation. The empirical part situates these ideas within the Polish context through the case of Kraków's Wesoła district − the example where statutory and strategic planning instruments (MPZP and Masterplan) were intentionally interwoven through participatory design. The Wesoła Masterplan (2024) translates global principles of critical design and operational urbanism into local practice, creating a "living laboratory" of adaptive governance, affective mapping, and co-creation.

The paper concludes that the most transformative potential of design today lies not in producing new forms but in cultivating the city's capacity to design itself − a planning culture based on reflection, experimentation, and shared knowledge.

Keywords: design-as-process; planning culture; High Line; urban living lab; sustainable development; regenerative urbanism; transfer of air rights

1. INTRODUCTION

Contemporary spatial planning is increasingly departing from a classical, control-oriented model based on maintaining spatial order and implementing local regulations. That model − whose principal aim was to "master the future" through prescriptive plans and drawings − proves inadequate in the face of today's multilayered climate, social, and infrastructural crises [Healey 2010]. In its place emerges a more

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relational and processual paradigm in which the city is understood not as a finished product but as an ongoing process of negotiating values, interests, and visions of the common good.

Within this shift − from plan as schema to planning as a learning process − design plays a pivotal role. It is no longer a terminal aesthetic gesture; rather, it acts as a medium of collaboration: a tool of mediation, a catalyst for consensus (or the revelation of conflict), and a language through which the city speaks about itself [Boelen 2015; Washburn 2013; Papanek 2021]. This shift in planning culture connects urbanism with design, legal, and social practices, redefining the role of the designer from maker of forms to organizer of processes and relations.

These transformations are particularly well illustrated by New York's High Line − one of the most influential urban projects of the early twenty-first century − in which design not only reshaped public space but also initiated a complex sequence of legal, social, and economic changes. The High Line became a prototype of operational urbanism − understood as a practice that binds together actors, regulations, and imagination [Forsyth 2024].

Against this backdrop, the article poses two core research questions:

a) In what ways did the High Line reframe relations among design, urban policy, and real-estate economics, particularly through the application of the Transfer of Development Rights (TDR)?
b) To what extent – and in what forms – do similar design logics appear in other cities worldwide, and what does their comparison reveal about the trajectory of contemporary planning culture?

Addressing these questions helps outline a new framework that understands design as a critical and epistemic process in which making space is simultaneously a social and political inquiry.

2. MATERIALS AND METHODS

The study combines a case-study approach with comparative analysis.

2.1. High Line Case Study

The analysis draws on source materials concerning the High Line's planning and design processes: documents of the New York City Department of City Planning, the Zoning Resolution, the report Reclaiming the High Line, materials by Friends of the High Line, and scholarly publications [Washburn 2013; Nelson i in. 2012].

The case study focuses on the role of design throughout the process − from civic action to the adoption of legal regulations and the implementation of the TDR instrument. The analysis is monographic, covering historical background, legal conditions, planning instruments, and spatial and social outcomes.

2.2. Comparative Analysis

The second level of inquiry is a comparative analysis of six contemporary urban projects in which design acted as a catalyst for urban transformation rather than a purely decorative tool of aestheticization. Case selection was based on procedural − not formal − similarity. The projects examined are:

a) **The Bentway (Toronto, Canada):** curated design under infrastructure.
b) **Cheonggyecheon Stream Restoration (Seoul, South Korea):** renaturalization as state narrative.
c) **Sewoon Maker City (Seoul, South Korea):** reactivation of inner-city making.
d) **Nordhavn (Copenhagen, Denmark):** integration of energy and spatial planning.
e) **King's Cross Regeneration (London, UK):** design leadership and mediation between public and private interests.
f) **SUPERTRENTO (Trento, Italy):** a participatory design laboratory.

Comparing these processes reveals shared features of a new planning culture: processuality, iterativity, co-creation, and the coupling of legal and affective tools. Methodologically, the article aligns with practice-led research [Boelen 2015], in which design is a form of inquiry − an approach to investigating social and spatial relations through action.

2.3. Research Methodology and Limitations

The research adopts a qualitative, interpretive approach characteristic of urban design research and practice-led research, treating the design process as a mode of knowing [Boelen 2015; Forsyth 2024]. It is based on document analysis, case analysis, and comparative interpretation. The objective is not quantitative hypothesis testing but a deepened understanding of relations among design, planning, and urban transformation.

Methods comprised:

a) a critical literature review in spatial planning, design theory, and operational urbanism, including canonical works [Healey 2010; Washburn 2013)] and contemporary reinterpretations [Boelen 2015; Awan 2023; Forsyth 2024];
b) a High Line case analysis grounded in municipal documents (Zoning Resolution, Friends of the High Line reports, court decisions, planning studies), design sources (Diller Scofidio + Renfro; James Corner Field Operations), and scholarly literature;
c) a comparative analysis of six cases across cultural and geographical contexts (Toronto, Seoul, Copenhagen, London, Trento), selected by procedural criteria: processuality, co-creation, mediation, and institutional innovation;
d) a synthesis of actionable insights for Polish planning practice based on translating concepts and tools from global to local contexts (e.g., urban living lab, governance canvas, design as project mode).

The study is qualitative and exploratory. Its findings are not universally generalizable − owing, among other factors, to the specificity and diversity of institutional contexts − yet they provide a basis for further comparative research and for testing methods in planning practice. The adopted methodology − document analysis, consultation processes, and case studies of design interventions − has been applied experimentally to the Kraków district of Wesoła, conceived as a laboratory of urban change.

Despite its limitations, the approach enables the reconstruction of spatial transformation logics, the identification of recurring mechanisms of mediation and innovation in urban planning, and the formulation of recommendations for Polish practice − especially regarding integration of strategic tools (masterplan) and regulatory instruments (Local Spatial Development Plan, MPZP) in the spirit of design-critical urbanism and an operational approach to the city.

3. CASE STUDY: THE HIGH LINE IN NEW YORK

3.1. Project Origins and Key Actors

The High Line did not emerge from a municipal program but from grassroots civic initiative. In the 1990s, the steel West Side Line viaduct on Manhattan's West Side − an out-of-use industrial railway − was slated for demolition. Joshua David and Robert Hammond founded Friends of the High Line (FHL) to save the structure and transform it into a new kind of public space: a linear park embedded in dense urban fabric.

From the outset, the project was narrative in character: it articulated an alternative future for the district that might escape the conventional logic of gentrification and developer-led uniformity [Washburn 2013: 97–100). FHL gained support from residents as well as from cultural and planning communities, including Amanda Burden, later Chair of the City Planning Commission.

In 2001, *The New Yorker* ran *Walking the High Line*, illustrated with Joel Sternfeld's photographs, triggering global attention. FHL then partnered with the Design Trust for Public Space and began preparing the *Reclaiming the High Line*report, which soon became the project's reference document.

3.2. Design and Law: Transfer of Development

The key instrument enabling implementation was the Transfer of Development Rights (TDR). Under this mechanism in American planning law, owners may transfer unused development rights from one parcel (the "sending site") to another (the "receiving site") to compensate for foregone development potential [Nelson i in. 2012: 25–28].

For the High Line, TDR was embedded in the Special West Chelsea District, established in 2005 under Article IX, Chapter 8, Section 98 of the New York City Zoning Resolution. This allowed property owners beneath the viaduct to sell their air rights to developers on nearby parcels, retaining financial benefits without needing to build on the rail corridor itself.

This solution acted as a "pressure valve" among the interests of the city, developers, and FHL: rather than fighting over demolition, a market in air rights reconciled the protection of public space with investment logic. Design − the visual and affective narrative of a green park on a viaduct − legitimized legal decisions and mediated between regulation and urban imagination [Washburn 2013: 141–149].)

3.3. Rezoning and Spatial Strategies

Preparing the Special West Chelsea District took more than three years and led to substantial amendments to zoning provisions. The main elements included:

a) creating a High Line Transfer Corridor to enable transfers of development rights between 19th and 30th Streets within a band roughly 30 meters wide;
b) introducing a mixed-use structure – combining residential, commercial, and cultural programs while preserving West Chelsea's artistic character (inclusionary zoning with a 20% share of affordable units);
c) regulating building envelopes (heights, setbacks, access to light) to protect the park experience.

The process exemplified institutional urban design – negotiated alignment of norms and interests.

3.4. Design Phase and Implementation

In 2004, the design competition was won by James Corner Field Operations, Diller Scofidio + Renfro, and Piet Oudolf. Their concept imagined the park as a "self-seeded city" – a space fusing industrial heritage with a new urban ecology.

In parallel, the Zoning Resolution amendments were finalized, and in 2005 the city acquired the viaduct (via a no-cost transfer from CSX Transportation). The first section opened in 2009, with subsequent segments in 2011 and 2014.

The outcome was spectacular: 2.33 kilometers of continuous green public space with more than 500 plant species forming a new ecological layer for the city. Equally significant, however, was the procedural dimension: the High Line altered how a city learns to plan itself [Boelen 2015; Forsyth 2024].

3.5. The High Line as a Laboratory of Planning Culture

From a planning-theory perspective, the High Line exemplifies reflective urbanism [Washburn 2013: 150–152] – a practice in which design helps pose better

questions about urban futures rather than simply provide ready-made solutions. The process is iterative and transdisciplinary:

a) bottom-up mobilization generates a vision;
b) public institutions learn legal flexibility;
c) design integrates economic, social, and symbolic rationalities.

The use of TDR demonstrates that urban innovation can be systemic rather than merely formal − designing institutional frameworks as well as spaces. In this sense, the High Line became an "urban laboratory" experimenting with a new model of co-governance (urban design leadership) [Brown 2024]. As Papanek [Papanek 2021: 231] observes, "good design not only solves problems; it helps us understand them." The High Line thus stands as a prime study in contemporary planning culture: design as an instrument of knowledge, not solely of form.

4. DISCUSSION—DESIGN AS AN URBAN TRANSFORMATION PROCESS

4.1. From the High Line to a New Planning Paradigm

Over the past two decades, an expanding array of urban projects has shown design not as aestheticization but as a strategy for organizing urban processes. The High Line inaugurated this paradigm, catalyzing a planning culture that is bottom-up, experimental, and integrative of policy, law, and imagination [Washburn 2013: 97–152].

Design ceased to be a final product and became a language of negotiation among heterogeneous actors − communities, investors, authorities, and the natural environment. This shift aligns with global trends that Albrechts [Albrechts 2021] and Healey [Healey 2010] term "strategic and reflective planning," wherein the city is not an object of management but a process of co-creation and learning. In this view, design is an epistemic instrument: it not only transforms space but also creates a shared language for describing and understanding change.

4.2. Reverberations of the High Line Model

The Bentway (Toronto): The space underneath.

Beneath Toronto's Gardiner Expressway, The Bentway − 1.75 km of public space developed incrementally since 2015 by The Bentway Conservancy in partnership with the city and private actors − positions design as a curator of social processes. Rather than a fixed form, it foregrounds cultural and infrastructural programming that activates space through events, exhibitions, and temporary interventions [Marsden 2022]. This is design "underneath" − operating in the shadow of infrastructure, turning marginal space into an urban stage and serving as a laboratory of inclusivity and negotiated visibility for marginalized groups.

Cheonggyecheon (Seoul): Re-nature as state narrative.

The removal of a 5.6-km elevated highway and the restoration of the Cheonggyecheon stream (2003–2005) created a new ecological and symbolic axis for Seoul. Initiated by Mayor Lee Myung-bak, it represents a top-down reinterpretation of the High Line model: the state "returns the river to the city," crafting a metropolitan development language through the aesthetics of water, cooling, and community [Cho 2023]. While the project delivered measurable climate benefits (microclimate, biodiversity), it has been criticized for a "spectacle of renaturalization" and gentrifying effects [Guillet 2014].

Interim takeaway. Both cases reveal design's duality: its capacity to build community and to generate new social tensions. Design is thus a political process, not merely an aesthetic one.

4.3. Design as Activation of Urban Ecosystems

Sewoon Maker City (Seoul): Infrastructures of collaboration.

In central Seoul, the revitalization of the Sewoon complex − once an electronics hub − redefined "revitalization." Sewoon Maker City (2015–2024) emphasized strengthening existing networks of making, craft, and micro-enterprise [Mun, Lee 2024], with design acting as collaborative infrastructure linking workshops, universities, and NGOs in a "maker city" model − an exemplar of practice-led urbanism.

SUPERTRENTO (Trento): Design as inquiry.

The Italian project SUPERTRENTO [Poggio et al. 2024] deploys a living-lab model in which residents co-produce urban scenarios ("Get informed – Imagine – Engage"). Here, design functions as a research tool rather than an executive one − structuring dialogue and prototyping urban experiments.

Interim takeaway. Sewoon and SUPERTRENTO mark a shift from spectacular to processual design: delicate urban acupuncture that fortifies existing ecosystems rather than replacing them..

4.4. Design as Governance

Nordhavn (Copenhagen): A sustainability laboratory.

The transformation of Copenhagen's Nordhavn into a "five-minute city" illustrates design as a vehicle for implementing public policy. The project integrates mobility, energy, and water systems in a unified, design-driven testbed [Haeusler, Schnabel 2023], functioning as a living laboratory where each spatial intervention is simultaneously a policy and social experiment.

King's Cross (London): Design leadership and patient capital.

The regeneration of King's Cross (2000–2020) exemplifies design-led governance, with design as a language mediating between public authorities, the developer (Argent), and local communities [Adams, Tiesdell, 2020; Brown 2024]. Beyond

a spatial plan, the project incorporated architectural quality control, sequenced delivery, and narrative stewardship – what the literature terms urban design leadership.

Interim takeaway. In Nordhavn and King's Cross, design serves as an institutional mediator – a governance tool coordinating complex relations among policy, market, and society.

4.5. From Design-Led to Design-Critical Urbanism

For years, "design-led regeneration" implied that good form guarantees social good. Experience from projects such as the High Line and Cheonggyecheon shows that design can become a tool of exclusion as readily as emancipation [Wallace 2024]. Hence the growing emphasis on design-critical urbanism [Awan 2023] − design as a practice of questioning and exposing power relations. Critical design does not negate aesthetics; it politicizes it − asking who benefits from space, who finances it, and who is displaced. From this perspective, the High Line, The Bentway, and Sewoon are critical experiments that not only create new spaces but also render conflicts and social tensions visible.

4.6. Operational Urbanism − The City as a Learning Process

Contemporary urban-planning theory [BioMed Central 2023; Forsyth 2024] conceives of the city as a system capable of self-transformation. Operating at the intersection of technology, ecology, and participation, design becomes a feedback mechanism: testing, correcting, and iterating change. Thus projects such as Nordhavn (energy laboratory), SUPERTRENTO (co-decision laboratory), and The Bentway (cultural laboratory under infrastructure) exemplify operational urbanism, where the city is an ongoing experiment. Design becomes less a spatial discipline than an organizational and social competence. As Boelen [Boelen 2015: 47] writes, "design is a way of making the world that simultaneously investigates it."

5. CONCLUSIONS AND IMPLICATIONS FOR POLISH PLANNING PRACTICE

5.1. From Static Plan to Planning Laboratory

The High Line and its contemporary reinterpretations demonstrate that twenty-first-century design has ceased to be an instrument of aestheticization and has become a language of mediation, integration, and inquiry. These projects reveal a decisive shift in planning culture: from control-based planning to curiosity-driven planning [Boelen 2015]. In practice, this reframes the city from something that is "designed" to something that designs itself through iterative processes of learning,

testing, and co-creation − a model we may call *design as project mode*. The city becomes a continuous laboratory of transformation where social, ecological, and affective knowledge is produced.

The following section situates this framework within the Polish context, using the Wesoła district as a testing ground for these principles.

5.2. A Polish Path − Wesoła as an Urban Laboratory

In recent years, the Kraków district of Wesoła has evolved from a conceptual testing ground into a real laboratory of urban transformation. Once envisioned as an "invisible city" − a suspended fragment between institutional past and undefined future − Wesoła has become one of the first sites in Poland where the principles of design-critical and operational urbanism are being institutionally implemented.

Following multi-stage participatory consultations conducted between November 2020 and February 2021 [Kryglon i in. 2021] and the adoption of the Local Spatial Development Plan (*Miejscowy Plan Zagospodarowania Przestrzennego – MPZP*) in December 2021 (Urząd Miasta Krakowa, 2021), the area became subject to an integrated planning and design process culminating in the *Masterplan for the Creative District Wesoła*, formally approved in late 2024 (Agencja Rozwoju Miasta Krakowa & Krakowskie Biuro Festiwalowe, 2024). This sequence − consultation, regulation, experimentation − illustrates a rare Polish example of a continuous planning cycle where civic knowledge, regulatory frameworks, and design imagination operate in feedback.

5.2.1. Living Laboratory

The 2024 Masterplan redefined Wesoła as a *green creative district (zielona dzielnica kreatywna)*: an open, inclusive, and processual environment combining cultural, ecological, and experimental dimensions. This shift was grounded in extensive participatory research carried out under the coordination of the Krakow Festival Office (KBF) and the City Architect's Bureau. The consultation report identified key collective values − *wytchnienie* (respite), *wspólnotowość*(community), *esperyment* (experiment), *dziedzictwo* (heritage), and *wielofunkcyjność* (multifunctionality) − which later structured the masterplan's five guiding principles.

Rather than a conventional regeneration project, Wesoła was conceptualized as a *laboratory of coexistence*, merging design practice with research and public education. Its governance structure – led by the City Architect, Agencja Rozwoju Miasta Krakowa (ARMK), and KBF – operates as a *quadruple-helix* platform integrating municipal institutions, universities, NGOs, and residents. This organizational model mirrors contemporary *urban living labs* in which spatial transformation becomes a collective epistemic process [Forsyth 2024; Healey 2010].

5.2.2. Design as an Epistemic and Affective Medium

The Masterplan explicitly embeds *soft mapping and affective diagnosis* into spatial policy. The design framework recognizes intangible dimensions − soundscapes, shade, smell, and emotional memory − as valid layers of planning evidence. This approach resonates with the article's earlier proposition of mapping the *invisible city* through sensory and affective cartographies [Boelen 2015]. In Wesoła, these are translated into concrete strategies: preservation of "quiet zones," design of *gardens of repose*, and blue-green infrastructures that reinforce ecological continuity with the nearby Botanical Garden and the former riverbed of the Old Vistula.

5.2.3. Processual Design and Iterative Implementation

The Wesoła Masterplan is structured as a ten-year staged process (2025–2035), with successive phases combining spatial adaptation, cultural programming, and infrastructural innovation. Early interventions − such as the establishment of the *Apteka Designu* (Design Pharmacy) and *Urban Forum* − already function as pilot nodes of operational urbanism. These initiatives prototype social and spatial innovations through workshops, temporary installations, and co-design experiments, embodying the logic of *design-as-research* [Forsyth 2024].

The iterative model aligns with the concept of *project mode* discussed earlier: each stage of transformation doubles as a research probe, generating feedback for the next. In this sense, Wesoła exemplifies the *learning city* paradigm [Healey 2010; Forsyth 2024], where planning evolves through reflection and adaptation rather than prescription.

5.2.4. From Regulatory Plan to Reflexive Governance

By juxtaposing the MPZP's prescriptive framework with the Masterplan's adaptive and narrative layer, Kraków demonstrates an emergent form of *reflexive governance*. The MPZP delineates the legal envelope of transformation – protecting historic structures, regulating heights, and safeguarding greenery – while the Masterplan operates as a curatorial and experimental instrument translating policy into lived urban culture. This dual structure marks a significant methodological innovation within Polish planning practice: for the first time, the statutory and the strategic have been intentionally interwoven through design [Albrechts 2021; Forsyth 2024]..

5.2.5. Implications for Design-Critical Urbanism

Wesoła's ongoing transformation thus extends the High Line's legacy into a Central-European context: design as a language of mediation between law, imagination, and community. It provides empirical evidence that the city's *invisible*

dimensions − memory, emotion, ecological rhythm − can be formalized within urban policy without losing their indeterminacy. As such, Wesoła stands as both a *case and a method*: a living demonstration that experimental, reflexive planning can coexist with formal regulation [Awan 2023; Boelen 2015; Healey 2010].

5.3. Operational Methods – Tools for Processual Design

A comparative reading of the High Line, The Bentway, Sewoon, Nordhavn, King's Cross, and SUPERTRENTO yields a toolkit adaptable to Polish planning as components of *operational urbanism*:

a) **Urban Living Lab.** A collaboration model linking universities, local government, designers, and communities. Instead of conventional consultations: a loop of testing, evaluation, and adaptation [Forsyth 2024] – planning not just for residents but with them.
b) **Urban Time-Boxing.** Temporary interventions with limited time horizons (e.g., 6–12 months) whose permanence depends on evaluation outcomes – a cadence of learning rather than procedure (as in The Bentway) [Marsden 2022].
c) **2×2 Design Scenarios.** Parallel ecological, social, economic, and cultural scenarios enabling participants to choose a direction of change rather than a single project – strengthening the city's reflective learning capacity *(design as research)* [Boelen 2015].
d) **Pilot Micro-Zoning.** Instead of large, comprehensive plans: small test zones with differentiated functions (green, education, production, culture), allowing relationships to be studied and successes scaled (Sewoon Maker City) [Mun, Lee 2024].
e) **Soft Urban Infrastructure.** Mapping intangible assets – social networks, emotions, memory, microclimate, sounds, data flows – integrated into planning processes, especially in "invisible" areas (e.g., Wesoła).
f) **Governance Canvas.** A workshop matrix of actor relations – public, private, civic, cultural – to identify tensions and synergies and design co-decision structures (King's Cross) [Brown 2024].

5.4. Toward a New Planning Culture – The Self-Designing City

Introducing these tools into Polish practice entails a shift from the *designed city* to the *self-designing city* − capable of reflexivity, experimentation, and responsiveness. It opens the way to a new planning culture that is reflective, critical, creative, and participatory. In this culture, design becomes a form of social knowledge − the means by which the city learns itself through actions, errors, and corrections. This is a design paradigm in which − as Papanek [Papanek 2021: 65] argued − "the designer does not solve problems but teaches us how to understand them better."

Polish cities face a challenge similar to New York's in the 1990s: how to combine economic, social, legal, and symbolic logics in a single process of spatial transformation. *Design-critical urbanism* offers a response: a practice that not only creates new spatial forms but also renders visible the relations, emotions, and forces that shape them.

In this sense, the Wesoła case brings the discussion full circle − from New York's High Line to Kraków's living laboratory − demonstrating that the most transformative aspect of urban design today lies not in creating new forms, but in cultivating the city's capacity to design itself.

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DESIGN JAKO KATALIZATOR TRANSFORMACJI URBANISTYCZNEJ: HIGH LINE W NOWYM JORKU, JEGO GLOBALNE REINTERPRETACJE I IMPLIKACJE DLA POLSKIEJ PRAKTYKI PLANISTYCZNEJ

Streszczenie

Artykuł podejmuje problematykę designu jako katalizatora transformacji miejskiej oraz jako narzędzia epistemicznego w ramach współczesnej kultury planistycznej. Analiza, oparta na przykładzie nowojorskiego projektu High Line oraz jego globalnych reinterpretacji – w tym The Bentway w Toronto, Cheonggyecheon w Seulu, Nordhavn w Kopenhadze oraz King's Cross w Londynie – ukazuje paradygmatyczne przesunięcie od designu rozumianego jako estetyzacja ku designowi pojmowanemu jako mediacja i współtworzenie. Przytoczone przykłady dowodzą, że projektowanie urbanistyczne funkcjonuje nie tylko poprzez kreowanie form przestrzennych, lecz także poprzez iteracyjne procesy zarządzania, obserwacji, uczenia się i negocjacji. Część empiryczna osadza te idee w polskim kontekście, analizując przypadek krakowskiej dzielnicy Wesoła – przykładu celowego powiązania instrumentów planowania ustawowego i strategicznego (MPZP i Masterplan) oraz projektowania partycypacyjnego. Masterplan dla Wesołej (2024) stanowi próbę przełożenia globalnych zasad designu krytycznego i urbanistyki operacyjnej na grunt lokalny, tworząc „żywe laboratorium” adaptacyjnego zarządzania, mapowania afektywnego i współkreacji. W artykule wykazano, że najgłębszy potencjał transformacyjny współczesnego designu nie polega na tworzeniu nowych form, lecz na rozwijaniu zdolności miasta do projektowania samego siebie – poprzez kulturę planowania opartą na refleksji, eksperymencie i współdzielonej wiedzy.

Słowa kluczowe: design jako proces, kultura planowania, High Line, laboratorium miejskie, zrównoważony rozwój, urbanistyka regeneratywna, transfer praw powietrznych

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ARCHITECTURAL GUIDELINES FOR STRENGTHENING STACK VENTILATION: PERFORMANCE INSIGHTS FROM URBAN HOUSING

Natural ventilation (NV) is a key energy-efficient strategy for improving indoor air quality and thermal comfort in residential buildings. In cold climates such as Poland, the dominant form of NV is stack (chimney) ventilation, whose effectiveness depends on temperature differences and wind conditions. The aim of this study was to evaluate the impact of different chimney configurations on air change intensity (ACH) in a real residential building in Gdańsk.

During a four-month measurement campaign, three solutions were compared: a traditional brick chimney (Type I), a solar chimney with a glazed extension (Type II), and a chimney equipped with a rotary cap (Type III). Results showed that, compared to the baseline configuration, the solar chimney increased the ACH by an average of 14% under favorable solar conditions, while the rotary cap improved ACH by up to 35% in moderate wind conditions.

The study confirms that even small passive modifications to chimneys can significantly enhance the stability and efficiency of stack ventilation. The findings provide practical design guidance for architects and urban planners, especially in the context of retrofitting existing buildings and designing new urban developments tailored to local climate conditions.

Keywords: stack ventilation, air change rate (ACH), solar chimney, chimney cap, urban housing

1. INTRODUCTION

Natural ventilation (NV) is a cost-effective and sustainable strategy for providing fresh air in residential buildings, contributing to thermal comfort, indoor air quality, and overall occupant well-being [Krishan 2001; Clarke 2001; Antczak-Jarząbska & Niedostatkiewicz 2017]. In urban environments, NV shapes the local microclimate and supports air circulation, enhancing comfort in densely built areas while improving environmental quality [Krishan 2001].

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In cold climates, stack ventilation—driven by buoyancy (stack effect) and wind—is the most common form of NV [LBNL 2007]. While effective under favorable conditions, its performance can be variable due to fluctuating wind and temperature differences [PN-B-03430:1983/Az3:2000; Antczak-Jarząbska & Niedostatkiewicz 2017]. Chimneys, as core elements of stack ventilation, play a dual role: they ensure proper airflow while influencing building aesthetics and the urban roofscape [Antczak-Jarząbska & Krzaczek 2016].

Design variations, including traditional brick chimneys, solar chimneys, or chimneys with rotary caps, can significantly impact ventilation efficiency. Quantifying these effects using the air change rate (ACH) allows for a measurable evaluation of airflow performance, providing actionable insights for architects seeking to balance functionality, comfort, and urban integration.

This study focuses on a residential building in Gdańsk, Poland, comparing three chimney configurations. Using ACH as a key metric, it evaluates how geometric and material differences influence airflow intensity and natural ventilation performance. The findings aim to inform design strategies for sustainable, comfortable, and visually integrated urban housing.

While previous Polish research on natural ventilation has largely emphasized airtightness and heat recovery [Nantka 2005], the influence of chimney design on stack ventilation efficiency in urban contexts remains underexplored. Recent studies highlight that modifications in building envelope and fenestration can improve indoor air quality and thermal comfort in multi-family buildings [Kwiatkowski et al. 2014], while integrating natural ventilation with passive strategies—such as solar chimneys—can reduce energy demand [Wójcik 2012].

By systematically assessing different chimney designs with ACH measurements, this study provides evidence-based guidance for architects and designers, supporting best practices in the planning of naturally ventilated urban residences under Polish climatic and architectural conditions. The importance of energy efficiency and passive design strategies has also been discussed in recent studies on the Polish residential building stock [Attia S., et al. 2022].

2. QUALITY OF STACK VENTILATION

The effectiveness of stack ventilation systems in residential buildings is commonly assessed using the air change rate (ACH) as the primary performance indicator. The ACH quantifies the frequency with which the total volume of indoor air is replaced by fresh outdoor air within a given time period. It serves as a crucial parameter for evaluating indoor air quality and ensuring compliance with ventilation standards in habitable spaces [Nantka 2005].

The stack ventilation rate, ACH(t) (h-1), according to the governing equation, depends on the airflow volume V(t) (m^3/s), the room cubature VR (m^3), and the dynamic

interaction of flow and pressure conditions within the system. Specifically, ACH is influenced by the instantaneous airflow leaving the ventilation system, the geometrical characteristics of the ventilated space, and the physical properties of the chimney configuration, including height, cross-sectional area, and surface roughness. The air change rate at a given moment *t* is calculated using the following equation (1):

$$\mathbf{ACH\ (t)} = \frac{\dot{\mathbf{V}}\mathbf{(t)} * \mathbf{3600}}{\mathbf{V_R}} \tag{1}$$

This formulation enables real-time or average assessment of ventilation performance, which is particularly valuable when testing different chimney configurations in full-scale or simulation-based studies. In naturally ventilated buildings, where airflow is influenced by fluctuating environmental conditions, this parameter allows for objective evaluation of system responsiveness and effectiveness in maintaining indoor air quality.

3. MATERIALS AND METHODS

In order to determine the influence of passive energy systems on the efficiency of stack ventilation, a series of in situ experiments were conducted in a representative residential building located in Gdańsk, Poland. The measurements spanned four months, from August to November, thereby covering both summer and early autumn climatic conditions typical of northern Poland.

The experimental object was a single-family residential building, chosen as representative of post-war Polish urban housing stock. A dedicated test room was designated within the building, equipped with a controlled air inlet and connected to a vertical ventilation duct (chimney). This configuration isolated the internal airflow from other building influences and ensured that the results reflected primarily the impact of external climatic factors. Such a controlled approach is particularly relevant, as studies focusing on chimney-induced ventilation efficiency in Polish urban residential buildings remain limited, despite the system's widespread use in traditional housing.

To monitor the environmental boundary conditions, a microclimatic weather station was installed in the immediate vicinity of the building. It continuously recorded outdoor temperature, wind speed and direction, solar radiation, and atmospheric pressure—factors known to influence the performance of natural ventilation systems driven by buoyancy (Wójcik, 2012; Zhai, & Previtali, 2010).

The central objective of the study was to measure and compare the air change rate (ACH) achieved under different chimney modifications designed to enhance stack-induced airflow. Three test configurations were implemented, each representing a distinct passive strategy relevant to contemporary architectural design (Fig. 1 schematic representations of the three chimney types):

- TYPE I – Traditional Chimney Configuration: A baseline case with a conventional ceramic brick ventilation duct extending above the roof.
- TYPE II – Solar Chimney Configuration: The above-roof chimney section was enclosed with transparent glazing, allowing solar radiation to increase the temperature differential and strengthen buoyancy-driven ventilation.
- TYPE III – Chimney Cap Configuration: A rotary chimney cap was installed on the Type duct, intended to enhance airflow extraction through wind-induced suction.

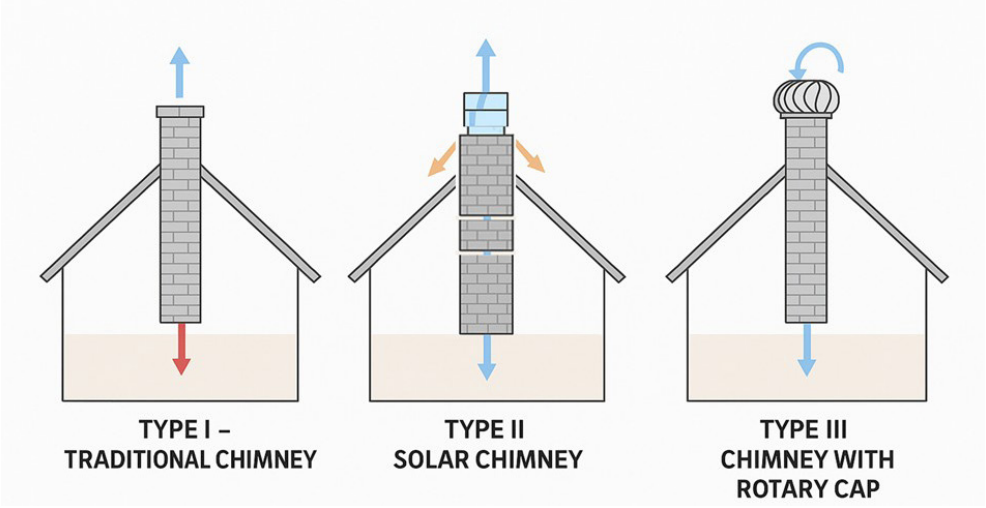

Fig. 1. Schematic representation of the three chimney configurations (Type I – traditional, Type II – solar, Type III – rotary cap) [from the author's collection]

Throughout all experiments, the positioning of airflow and temperature sensors inside the test room and along the ventilation duct remained constant, ensuring the comparability of results across different configurations.

The test building is a two-storey, two-apartment residential house located in Gdańsk (northern Poland, cold climate zone). The selected apartment (floor area ≈ 50 m²) was situated on the first floor and included a kitchen, living room, bedroom, bathroom, and corridor. For measurement purposes, only the kitchen was designated as the test space, while other rooms were isolated from the ventilation system. The apartment remained inhabited during the campaign, with residents' activities occurring primarily in the morning and after 5:00 pm.

Constructed in the 1950s and renovated in 2012, the house represents a typical example of Poland's urban residential architecture, characterized by heavyweight construction with concrete floor slabs and stone cavity walls. Table 1 presents the thermal properties (U-values) of the main structural components.

The choice of such a case study reflects the prevalence of similar housing stock across Polish cities and underscores the relevance of stack ventilation solutions for everyday architectural practice.

By addressing real conditions in a representative Polish urban building, this study not only provides empirical evidence on the performance of stack ventilation systems but also highlights practical implications for architectural and urban design. The findings inform architects, engineers, and urban planners about the integration of passive ventilation strategies into both new construction and the modernization of existing housing stock. In particular, the inclusion of alternative chimney configurations—such as solar chimneys or chimneys equipped with rotary caps—can significantly strengthen the stack effect, enhance air exchange stability, and improve indoor air quality [Bręczewska-Kulesza 2009]. For designers, this underlines the importance of considering chimney geometry, materials, and additional aerodynamic elements already at the conceptual stage of the project [Antczak-Jarząbska & Krzaczek 2016].

The test apartment was equipped with a stack ventilation system with controlled air inlets and chimney ducts. The air inlets were small devices mounted in the casement or window frame, regulating the inflow of fresh air. This solution, first introduced in Scandinavia in the 1960s, has since been widely implemented across Europe [Andersen 1992: 23]. In Poland, inlet gaps are obligatory in buildings utilizing stack ventilation combined with multi-chimney ducts [PN-B-03430:1983/Az3:2000].

In the studied apartment, the air inlet to the chimney duct was additionally equipped with a controllable vent grill positioned 0.15 m below the room ceiling. The measurement system was restricted to the kitchen (Fig. 2), with a usable area of 15.75 m^2 and an air volume of 40.95 m^3. The simplified set-up—with one air inlet (rectangular gap integrated into the window frame) and one air outlet (kitchen chimney duct)—reduced the number of unknown variables influencing the air exchange process. The used air was removed through a vent with dimensions of 0.14 × 0.14 m. During the measurement period, all windows were closed, and internal doors remained shut during night-time and residents' work hours.

The case study demonstrates that, while conventional brick chimneys remain effective in standard residential conditions, the introduction of modern variations—solar-assisted chimneys, double-duct systems, or chimneys with aerodynamic caps—can offer architects additional design flexibility and higher robustness of natural ventilation under variable climate conditions [Bansal et al. 1994; Zhai & Previtali 2010]. As urban housing density increases, the deliberate choice of chimney type may become a key architectural tool for balancing aesthetic integration with functional performance.

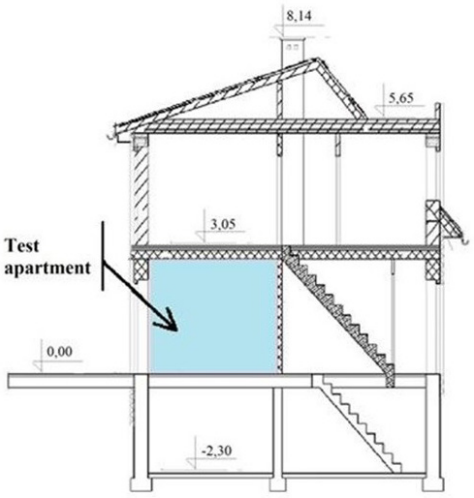

Fig. 2. The residential family test house vertical section of the first floor [from the author's collection]

The test room was equipped with a single-chamber PVC window with dimensions 4/16/4 mm. The room had two doors, each opening to a heated adjacent space. When residents were absent, the doors were tightly sealed. The chimney itself was built using traditional full ceramic brick technology. In TYPE I, the chimney extended 1.04 m above the roof slope. The external wall was made of solid ceramic brick with a total thickness of 0.38 m, while internal partition walls were 0.12 m thick.

In TYPE II, the section of the chimney protruding above the roof was enclosed with a transparent float-glass cover, with a 0.04 m air gap. The glazing consisted of 5 mm thick glass panes. This design aimed to enhance buoyancy forces by utilizing solar radiation, while the remaining elements of the ventilation system were unchanged. The material and thermal parameters of the partitions for this configuration are summarized in Tab. 1.

Tab. 1. The material and thermal parameters of the partitions in the ventilation system

Element	Thickness d [m]	Thermal conductivity λ [W/mK]	Emissivity e [-]
Window joinery	0,024	1,4	0,95
External wall	0,38	0,77	0,84
Chimney wall	0,12	0,77	0,84
Glass wall	0,005	6	0,95
Air gap	0,04	0,025	–

Source: from the author's collection

In TYPE III, a rotary-type chimney cap was installed on the traditional chimney described in TYPE I. The cap was expected to improve airflow extraction through wind-induced suction, offering a low-cost and practical modification for improving natural ventilation efficiency in existing residential buildings. Fig. 3 representation of the three chimney types in reality:

Fig. 3. Real type of the three chimney configurations (Type I – traditional, Type II – solar, Type III – rotary cap) [from the author's collection]

By comparing these three configurations, the study addresses a significant research gap in Polish residential architecture, where experimental assessments of chimney-induced ventilation under real urban conditions are scarce. The findings are intended to guide architects and urban planners in evaluating how small-scale design interventions—such as solar chimneys or aerodynamic caps—can improve indoor air quality and contribute to more sustainable urban housing strategies. The measurement system enabled continuous monitoring of indoor and outdoor climate conditions, as well as airflow velocity in the vent inlets and outlets. It consisted of calibrated thermo-anemometers, pressure and temperature sensors, a weather station, and data acquisition software (LAB-EL LBX 2012). Measurements were logged in real time and stored in an SQL database. The local climate station was installed on the roof of the test building to record wind speed and direction, temperature, humidity, barometric pressure, and solar radiation. This setup ensured that airflow variations could be directly linked to external climate drivers [Shi, Yuan, Chen, & Angeli, 2015; Wójcik, 2012].

The experiment lasted from August to November, covering variable seasonal conditions in northern Poland. Outdoor temperatures ranged from –0.4 °C to 32.8 °C, with an average of 11.4 °C. Wind conditions were generally weak, with an average velocity below 0.8 m/s. The dominant wind direction was north (58%), while solar radiation frequently exceeded 100 W/m² during daytime hours, favoring solar chimney performance [Zhai & Previtali, 2010].

4. VENTILATION EFFICIENCY AND ARCHITECTURAL GUIDELINES

The comparative analysis of three chimney types—traditional, solar, and rotarycap—demonstrates that relatively simple passive modifications can significantly enhance stack ventilation efficiency in Polish urban housing. While the baseline configuration achieved an average ACH of 0.61–0.67 1/h, the introduction of a solar chimney improved airflow by approximately 14% under conditions of low wind and sufficient solar radiation, whereas the rotary cap increased performance by up to 35% in moderate wind conditions. These findings confirm that chimney geometry, materials, and aerodynamic adjustments directly affect ventilation stability and intensity [Liddament 1996; Bansal, et al. 1994; Ji, Cook & Hanby 2003; Antczak-Jarząbska & Niedostatkiewicz 2017; Zhai & Previtali 2010]. For architects and urban planners, the results highlight the need to consciously select chimney types suited to local climate, urban morphology, and building typology. Solar chimneys are particularly recommended in compact developments with limited wind exposure, while rotary caps are advantageous in areas with moderate wind, offering low-cost retrofitting opportunities. Furthermore, attention should be paid to chimney height (minimum 1 m above the roof ridge), material durability (ceramic, glass, or corrosion-resistant metals), and integration with architectural form, so that ventilation elements become both functional enhancers of air change rate and expressive accents of the roofscape. At the urban scale, the systematic application of such solutions can contribute to improved microclimate regulation, reduced reliance on mechanical ventilation, and mitigation of the heat island effect [Bręczewska-Kulesza 2009].

5. CONCLUSIONS

The analysis of three chimney configurations demonstrated that even relatively simple modifications can significantly enhance the efficiency of stack ventilation in Polish residential buildings. The traditional chimney (Type I) provided only limited performance under transitional climatic conditions, while both the solar chimney (Type II) and the rotary cap chimney (Type III) substantially improved air exchange rates. These findings lead to several practical guidelines relevant for architects and urban planners:

- Selection of chimney type should be aligned with local climatic and urban conditions. In dense urban areas with restricted airflow, solar chimneys allow the use of solar energy to reinforce the stack effect. Rotary caps, on the other hand, are effective in regions with moderate wind speeds, stabilizing system performance and reducing fluctuations in air exchange.
- Geometric and material parameters play a decisive role in system efficiency. Chimneys should extend at least 1 m above the roof ridge to ensure sufficient

draft. Materials with high thermal mass, such as ceramic brick, support stable airflow, while glazed surfaces in solar chimneys maximize solar heat gain and intensify buoyancy-driven ventilation.

- Architectural and aesthetic integration should be considered as both a technical and cultural issue. Chimneys—traditional or modern—contribute to the roofscape and urban identity. Rotary caps can introduce kinetic elements, highlighting the building's environmental responsiveness, while solar chimneys can serve as vertical accents, merging traditional forms with contemporary energy strategies.
- Urban-scale implementation of enhanced stack ventilation systems can improve microclimatic conditions. Systematic use across multiple buildings helps reduce reliance on mechanical ventilation, mitigate urban heat island effects, and contribute to sustainable urban planning.
- Operational and maintenance aspects must be anticipated at the design stage. Easy access to chimney elements enables cleaning and inspection, while the selection of durable, climate-resistant materials ensures long-term functionality under wind, frost, and snow loads.
- In summary, the design of chimneys should not be treated solely as a technical necessity but as an opportunity to consciously shape both residential environments and the wider urban landscape. Incorporating innovative chimney types—such as solar and aerodynamic systems—can enhance stack ventilation performance, enrich architectural expression, and support sustainable development strategies.

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WYTYCZNE ARCHITEKTONICZNE DOTYCZĄCE WZMACNIANIA WENTYLACJI KOMINOWEJ: WNIOSKI Z BADAŃ NAD WYDAJNOŚCIĄ W ZABUDOWIE MIEJSKIEJ

Streszczenie

Naturalna wentylacja (NV) stanowi kluczową, energooszczędną strategię poprawy jakości powietrza wewnętrznego i komfortu cieplnego w budynkach mieszkalnych. W klimacie chłodnym, takim jak w Polsce, dominującą formą NV jest wentylacja grawitacyjna (kominowa), której efektywność zależy od różnic temperatur oraz warunków wietrznych. Celem niniejszego badania była ocena wpływu różnych konfiguracji kominów na intensywność wymiany powietrza (ACH) w rzeczywistym budynku mieszkalnym w Gdańsku. W ramach czteromiesięcznej kampanii pomiarowej porównano trzy rozwiązania: klasyczny komin murowany (Typ I), komin solarny z oszkloną nadbudową (Typ II) oraz komin z obrotową nasadą (Typ III). Wyniki wykazały, że w porównaniu do konfiguracji podstawowej, komin solarny zwiększał ACH średnio o 14% przy sprzyjającym nasłonecznieniu, natomiast komin z nasadą – o 35% przy umiarkowanym wietrze. Badanie potwierdza, że nawet niewielkie, pasywne modyfikacje kominów mogą istotnie poprawić stabilność i wydajność wentylacji grawitacyjnej. Wyniki dostarczają praktycznych wskazówek projektowych dla architektów i urbanistów, zwłaszcza w kontekście modernizacji istniejących budynków oraz projektowania nowej zabudowy miejskiej z uwzględnieniem klimatu lokalnego

Słowa kluczowe: wentylacja, wskaźnik wymiany powietrza (ACH), kominy słoneczne, nasada kominowa, mieszkalnictwo miejskie

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PROBLEMS OF CONSERVATION AND REPAIR OF THE WALL CRESTS OF THE JANOWIEC CASTLE ON THE VISTULA RIVER

Wall crests are the parts of historic masonry structures most exposed to the destructive effects of atmospheric and biological factors, which, in the case of the Janowiec Castle—constructed primarily of limestone opoka—results in accelerated degradation. The authors present the development of conservation methods, ranging from historical attempts involving turf coverings and epoxy resins, through technical–biological solutions, to contemporary techniques based on capping masonry, grouting, and insulation systems.

The history of the castle is outlined, from its construction in the 16th century as the Firlej family residence, through wartime destruction and later utilitarian use, to conservation and protective measures undertaken since the 1970s. Emphasis is placed on the importance of preserving ruins with minimal intervention into the original historic fabric.

The technical condition assessment revealed serious damage, including erosion of the limestone opoka, loss of mortar joints, biological corrosion, frost and salt damage, as well as the negative effects of earlier repairs carried out with cement-based mortars. A comparison of documentation from 2010 and 2025 demonstrates ongoing degradation and an increasing level of risk to both the structural stability of the walls and visitor safety.

In the design section, comprehensive solutions are proposed, including masonry rebuilding and strengthening injections, quartzite capping with insulation layers, and protective measures using lead sheet coverings and ceramic fittings. Methods already tested at Janowiec are recommended, as they combine technical effectiveness with the preservation of authenticity and the legibility of the historic structure.

In conclusion, the authors emphasize the need to implement an integrated conservation programme encompassing repairs, monitoring, and systematic maintenance in order to ensure the long-term protection of this exceptional monument.

Keywords: Janowiec Castle; wall crests; conservation of ruins; limestone opoka; wall degradation; wall protection; conservation techniques; defensive architecture; heritage protection; permanent ruin

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1. INTRODUCTION

Wall crests, as the most exposed elements of historic structures, are particularly vulnerable to the destructive effects of atmospheric factors such as precipitation, wind, ultraviolet radiation, and freeze–thaw cycles [6]. Their proper protection constitutes one of the key components of a long-term conservation strategy for historic masonry. Leaking or degraded wall crests facilitate the infiltration of rainwater, which leads to the deterioration of mortar joints and masonry materials [3], and consequently to the weakening of the entire structure. This problem is especially evident in buildings that have remained in a state of ruin for extended periods, such as the Castle in Janowiec on the Vistula River.

In Polish conservation literature, this issue has been addressed, among others, by Domasłowski and Szmidel-Domasłowska [5], who analysed the impact of weathering on wall crests and methods of their strengthening, including the use of protective superstructures and appropriate lime mortars. Their approach provided a point of departure for subsequent material and technological studies. Przyłęcki [11], in turn, emphasised the importance of adequate horizontal protection and the application of capping masonry made of materials compatible with the historic structure, highlighting the need to design technical solutions in close relation to the architectural context of the monument.

In recent years, this subject has become the focus of interdisciplinary research combining conservation science, geology, materials engineering, microbiology, and digital heritage documentation [8]. Particular emphasis is placed on understanding the microstructure of building materials and their response to environmental conditions, especially in the case of highly porous materials such as limestone opoka. Research on biodeterioration also indicates the necessity of controlling biological growth on wall crests and employing biologically mild conservation agents.

In Poland, contemporary methods of protecting wall crests have been analysed, among others, by Trochonowicz [16], who, with reference to bastioned structures in the Lublin region, such as Janowiec, presented complex conservation problems related to limestone opoka as the primary building material. He drew attention to its high porosity, low resistance to alternating freeze–thaw cycles, and susceptibility to biodeterioration and chemical pollution. The author points to the need for integrated diagnostic methods, including non-destructive testing, photogrammetric documentation, and microbiological analyses. The conservation of such masonry requires an individual approach to each section of the wall crest, depending on its history of use, degree of deterioration, and function within the current composition of the ruins.

International experience also provides valuable insights. Examples of wall crest conservation in German, French, and Italian castles demonstrate that success in this field depends on the synergy between traditional methods and modern composite materials, as well as advanced documentation techniques [3].

In light of these considerations, studies addressing the technical condition and repair methods of the wall crests of the Janowiec Castle acquire particular significance. The monument, under the care of the Nadwiślańskie Museum, has for many years served as a model example of a permanent ruin, the conservation of which requires a balanced approach in accordance with the principle of minimal intervention while maximising the preservation of original fabric. The need for a comprehensive approach to wall crest protection is confirmed by numerous Polish and international publications. As early as the 1960s, the classic study by Domasłowski and Szmidel-Domasłowska [5] highlighted the destructive impact of atmospheric conditions and the necessity of experimental protective methods, such as the use of epoxy resins. Another important contribution is the article by Przyłęcki [11], which introduced an innovative turf-based protection method for wall crests, referred to as a technical–biological approach.

Tajchman [15] analysed doctrinal aspects of ruin conservation and discussed the importance of wall crest protection in the context of differences between Polish and English conservation approaches. Jasieńko et al. [9] presented the results of field and laboratory investigations that identified the most common causes of degradation and compared the effectiveness of various protection methods.

Studies by Trochonowicz and Szmygin [18] emphasised the complexity of degradation processes and the importance of material compatibility and aesthetic considerations in conservation interventions. In subsequent research, Trochonowicz and Drobek [17] carried out a comparative analysis of several Gothic castles, demonstrating the long-term effectiveness of the applied methods in protecting wall tops.

In the international context, it is also worth noting the research by Hanssen and Viles [8], who conducted an experimental analysis of the impact of soft vegetative coverings (soft capping) on rainwater runoff. The classic monograph by Ashurst [1] discusses the methodology of the English school of ruin conservation and highlights the significance of wall crest conservation as an element in preserving structural authenticity.

In Poland, contemporary interventions in castle ruins, including wall crest protection, have also been widely discussed. An example is the chapter by Głuszek [7], which addresses aesthetic and functional dilemmas. Stępień [12] likewise presents specific examples of implemented solutions. Szmygin [14] summarises national conservation experience, identifying key problems and good practices. A historical reference remains the classic publication by Cohausen [4], who was among the first to advocate the use of turf to protect wall crests from water. Taken together, these sources provide a solid basis for further conservation analysis of wall crest protection in the context of the Janowiec Castle.

2. HISTORY OF THE JANOWIEC CASTLE

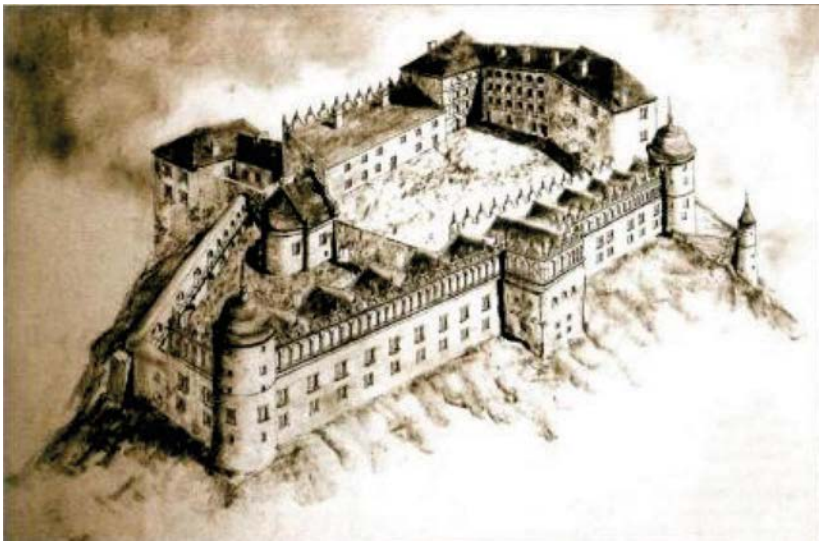
The Castle in Janowiec on the Vistula River was constructed between 1508 and 1526 on the initiative of Mikołaj Firlej, Voivode of Lublin, as a representative magnate residence with defensive functions, situated on a high escarpment overlooking the Vistula River. The structure was built using locally available materials—limestone opoka, brick, and sandstone—and its architecture reflects the influence of the Italian Renaissance, associated with the owners' contacts with European artists and architects [21].

Rys. 1 The Castle in Janowiec on the Vistula River. Drawing by E. J. Dahlberg, 1656.

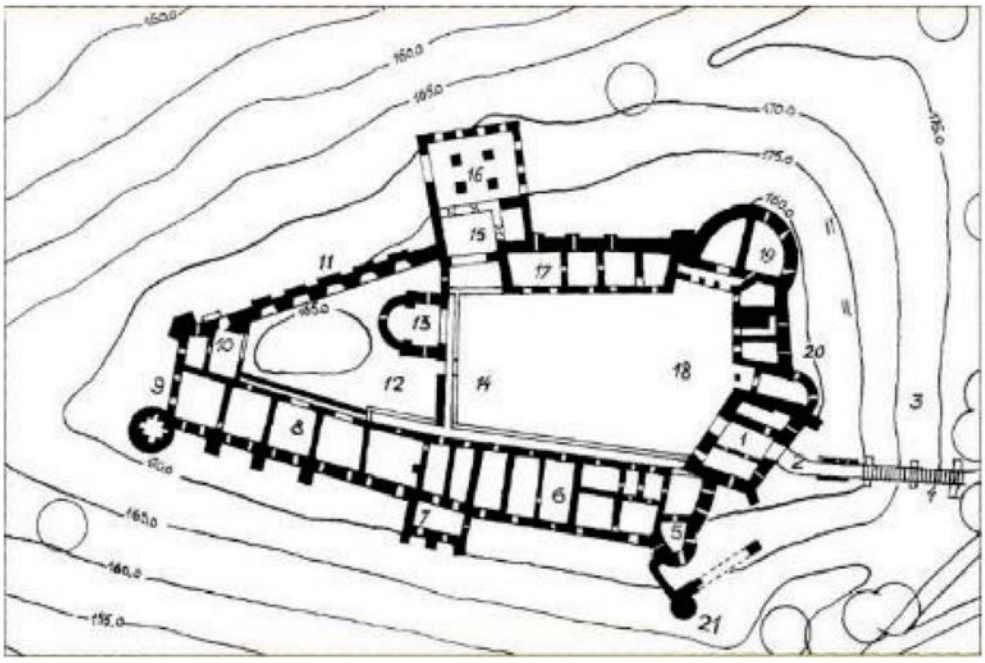
In the second half of the 16th century, the founder's son, Piotr Firlej, continued the construction works, giving the castle a regular courtyard layout and expanding the fortifications in accordance with the principles of early modern bastioned defensive architecture. The castle later passed into the hands of other prominent families, such as the Tarło and Lubomirski families, who introduced new architectural elements. Particularly significant was the contribution of artists such as Santi Gucci—the author of the Renaissance stonework—and Tylman van Gameren, who was responsible for Baroque transformations of the interiors [21].

Rys. 2 Reconstruction of the castle's appearance in the first quarter of the 16th century. View from the south-west. Drawing by T. Augustynek, 1994.

In 1656, the castle was severely damaged during the Swedish Deluge, and its reconstruction was never completed. In the 18th and 19th centuries, the castle was used for utilitarian purposes (as a granary and barn), and its structural elements served as a source of building materials [21].



Rys. 3 Reconstruction of the castle's appearance in the third quarter of the 17th century. View from the south-west. Drawing by T. Augustynek, 1994.



Rys. 4 Castle plan: 1. Gatehouse, 2. Gate neck, 3. Moat, 4. Bridge, 5. Eastern tower (originally a puntone bastion), 6. Southern enfilade, eastern part (Andrzej Firlej Palace), 7. Southern residential tower (southern risalit), 8. Southern enfilade, western part (Tarło Palace), 9. Western tower, 10. Western apartment, 11. Northern defensive wall, 12. Small Courtyard, 13. Chapel with well, 14. Cloisters, 15. Northern residential tower (demolished in the 17th century), 16. Servants' quarters (northern outbuilding), 17. Northern House, 18. Great Courtyard, 19. Great bastion, 20. Eastern wing, 21. Small tower on the subwall. Drawing by T. Augustynek, 1995.

A new chapter in the history of the monument began in 1931, when the castle was purchased by Leon Kozłowski—an art historian and archaeologist—who undertook the first attempts to protect the site. After the Second World War, the castle fell into increasing ruin until, in 1975, it came under the care of the Nadwiślańskie Museum in Kazimierz Dolny. Since that time, architectural and archaeological research, as well as gradual protective works, have been carried out [13].

Technical measures to secure the castle ruins commenced in 1976. Initially, ad hoc protective measures were applied, including temporary props, tensioned cables, and provisional masonry infills.

In 1978, following the preparation of the first design documentation for the eastern wing by the Warsaw branch of PKZ (State Enterprise for the Conservation of Monuments), the implementation of permanent protective measures began. However, in 1988, the museum abandoned the PKZ concept, considering it to involve excessive interference with the historic fabric due to the use of modern structural solutions.

The services of PKZ as a contractor were also discontinued, and the works were entrusted to local craft workshops.

Between 1988 and 1994, intensive conservation activities were carried out, resulting in the structural stabilisation and conservation of approximately 90% of the castle walls. Weathered wall crests were strengthened with quartzite, a material harder than the chalky limestone opoka; window and door lintels were rebuilt; and

Photo 1 Wall of the gate neck. 2010.

Photo 2 View of the courtyard and the southern enfilade.

structural solutions such as concealed reinforced concrete ring beams, prestressing, and bonded anchors were applied. All works were conducted in such a way as to minimise interference with the original structure. In 1995, the reconstruction of the Northern House was completed; it was erected almost entirely on preserved historic foundations and currently serves a conference and museum function.

Today, the Janowiec Castle represents one of the best-documented examples of permanent ruin conservation in Poland. It is not only an important example of Renaissance residential–defensive architecture, but also a valuable field for contemporary conservation, architectural, and archaeological research.

3. TECHNICAL CONDITION

The technical condition of the wall crests of the Janowiec Castle on the Vistula River must be assessed as seriously endangered, with the scale and character of deterioration varying depending on location, exposure, and the original building material. The upper sections of the perimeter and bastioned walls, which are particularly exposed to direct precipitation, wind, freeze–thaw cycles, and solar radiation, show clear signs of advanced degradation. This deterioration includes both material losses and structural damage.

In many sections of the wall crests, symptoms of loosening and structural disintegration are evident: individual stones have become displaced, and cracks and transverse fissures have developed, leading to a loss of cohesion within the masonry. The binding mortar frequently crumbles, facilitating further moisture penetration and intensifying destructive processes. Particular attention should be paid to numerous surface cavities and losses, some of which reach depths of several centimetres and pose a direct threat to the stability of the wall tops.

In many areas, intensive stone erosion is also observed, especially of limestone opoka, which constitutes the primary building material of the castle. As a sedimentary rock with high porosity and low cohesion, opoka is particularly susceptible to scaling, cracking, and delamination. Under the influence of prolonged moisture exposure, ultraviolet radiation, and temperature fluctuations, this material loses its integrity, in extreme cases leading to the detachment of entire stone surfaces. The masonry structure also contains sandstone and brick elements, which deteriorate to varying degrees depending on firing quality, water absorption, and exposure to moisture.

The effects of earlier technical and conservation interventions are also visible and, in many cases, were carried out in a manner inconsistent with contemporary principles of heritage conservation. The use of cement-based mortars with excessive stiffness and alkalinity has contributed to the development of local stresses and microcracking in adjacent areas of the original fabric. The replacement of missing material using stone incompatible in terms of structure, colour, and technical

properties has resulted in zones exhibiting differential behaviour under service conditions.

A systemic problem remains the lack of effective drainage of rainwater from the wall crests, leading to their long-term moisture retention. The presence of mosses, lichens, and higher vegetation (such as grasses, herbs, and in some locations even self-seeded trees) indicates persistent moisture in the near-surface zone, which in turn results in biological corrosion of the masonry material and a reduction in its mechanical properties. Capillary rise, typical of walls lacking horizontal damp-proof courses, further exacerbates the problem by enabling the transport of moisture and salts from lower parts of the wall upwards. Salt crystallisation within micropores generates secondary internal stresses and promotes further delamination.

Numerous freeze-affected zones are also evident—primarily on the northern elevations of the walls—manifesting as networks of microcracks and degradation of facing surfaces. During winter freeze–thaw cycles, material expansion occurs, particularly in porous opoka, leading to structural losses and the detachment of entire fragments. As a structural system, the wall loses cohesion, and its static stability may be compromised, especially in areas where mortar loss, stone erosion, and stresses resulting from previous unsuccessful repairs occur simultaneously.

Based on the overall assessment, it must be unequivocally stated that the wall crests of the Janowiec Castle require urgent and comprehensive remedial intervention. The current state of preservation not only diminishes the visual and exhibition value of the monument but also poses a real threat to its durability and to the safety of individuals present within the ruins. It is therefore necessary to implement a repair programme that addresses both structural and conservation aspects, in accordance with the principles of preserving the authenticity of historic fabric and ensuring long-term structural stabilisation.

Additionally, on the basis of two site inspections and photographic documentation prepared in 2010 and 2025, an analysis of changes in the technical condition of the walls over the past 15 years was carried out.

Analysis of the photographic documentation indicates the following:

- In several locations, additional temporary protective structures have been installed to secure the most severely degraded sections of the walls.
- Within the castle grounds, the number of fenced-off areas restricting tourist access has increased.
- Intensive deterioration of the low (secondary) walls of the southern enfilade has been observed. Damage is most pronounced in areas where quartzite capping was not applied.
- A clear increase in the number of failures of the mortar bonding the secondary quartzite capping at the interface with both secondary and historic layers of limestone opoka masonry.
- Significant degradation of the mortar beneath the wall crests in areas where damage had previously occurred; the cracks have reached markedly larger dimensions.

Locally (e.g. in the chapel walls), the capping masonry has become completely detached from the limestone opoka wall core. This condition may pose a safety risk to people in the vicinity of the walls.

- An increase in the number of defects caused by salt crystallisation and frost damage on the surfaces of the wall faces.
- A larger surface area affected by biological corrosion (algae, lichens, mosses). New damage to the wall crests allows greater quantities of water to penetrate into the masonry. Excessive moisture promotes more intensive biological deterioration.
- A significantly greater number of locations where annual and perennial vegetation has developed. Plant root systems cause intensive degradation of the masonry material..

Photo 1 Wall of the gate neck. 2010.

Photo 2 Wall of the gate neck. 2025.

Photo 3 Wall connecting the gatehouse and the eastern tower. 2010.

Photo 4 Wall connecting the gatehouse and the eastern tower. 2025.

Photo 5 Southern enfilade, eastern part (Andrzej Firlej Palace). 2010.

Photo 6 Southern enfilade, eastern part (Andrzej Firlej Palace). 2025.

Photo 7 Remains of walls adjacent to the southern enfilade, western part (Tarło Palace). 2010.

Photo 8 Remains of walls adjacent to the southern enfilade, western part (Tarło Palace). 2025.

Photo 9 Southern residential tower (southern risalit). 2010.

Photo 10 Southern residential tower (southern risalit). 2025.

Photo 11 Northern defensive wall. 2010.

Photo 12 Northern defensive wall. 2025.

Photo 13 Postern gate between the Great and the Small Courtyard. 2010.

Photo 14 Postern gate between the Great and the Small Courtyard. 2025.

Photo 15 Chapel with a well. 2010.

Photo 16 Chapel with a well. 2025.

Photo 17 Quartzite capping of the chapel wall crest. 2010

Photo 18 Quartzite capping of the chapel wall crest. 2025

Photo 19 Walls of the servants' quarters (northern outbuilding). 2010.

Photo 20 Walls of the servants' quarters (northern outbuilding) 2025.

Photo 21 Wall connecting the Great Bastion and the Northern House. 2010.

Photo 22 Wall connecting the Great Bastion and the Northern House. 2025.

4. METHODS OF WALL PROTECTION

Works related to the protection of wall crests are often combined with their partial or complete reconstruction. The selection of a specific method depends on the assumptions of the conservation programme as well as on a number of factors, including the type of wall, its state of preservation, structural system, materials used, and the architectural and conservation concept adopted for the entire monument. Each solution differs in terms of durability, degree of intervention in the historic fabric, legibility, and reversibility.

Application of a new layer on the wall crest. These solutions involve introducing a new layer that absorbs the impact of destructive factors and, in the event of degradation, can be periodically replaced. This group includes:

- Reconstruction of wall sections – a form of permanent protection achieved by rebuilding missing fragments, sometimes up to their historic height. Indigenous or similar materials are used, differing only in detail (colour, format, jointing technique). Three variants may be distinguished:
  - Reconstruction to the original height, incorporating elements of defensive architecture (crenellations, parapets, walkways, roofing).
  - Reconstruction to a height lower than the original, finished with a straight termination, with or without additional roofing.
  - Reconstruction below the historic height, preserving the irregular plasticity of the ruins.
- Capping masonry (overbuilding) – supplementation of the upper part of the wall with several courses of brick or stone. The material may be local or non-local; however, excessive visual contrast may create an impression of artificiality. Capping does not halt degradation but rather "transfers" its effects to the new layer. It may be executed with an insulation layer (providing better protection and easier dismantling) or directly on the historic masonry.
- Protection with mortars or concrete – the execution of a tight protective layer on the wall crest, with the possibility of forming slopes to facilitate water runoff. This is an effective solution, although in the case of low walls it may be perceived as less aesthetically pleasing.
- Technical–green method – the intentional planting of vegetation (e.g. shallow-rooted grasses) on the wall crest following surface levelling and preparation. This method requires regular maintenance and involves the risk of the development of unwanted plant species.
- Protection by covering the wall crest. The aim of these methods is to limit the impact of rainwater. They may be temporary or permanent and include:
- Roofing structures – constructions designed to protect the wall crest from rainfall. These may be temporary (made of various materials and applied locally) or permanent, adapted to tourist use. They are executed, among others, using roof tiles, metal sheets, laminates, or supported by structures without permanent anchorage to the wall.

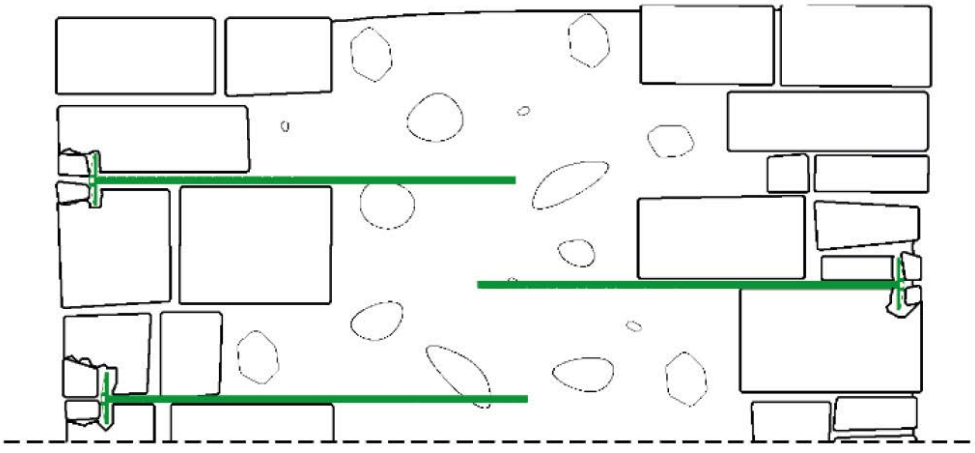
- Chemical protection – hydrophobisation or surface sealing using specialist preparations. This method requires careful substrate preparation, appropriate selection of the agent for the specific material, and adherence to suitable application conditions.

5. PROPOSED METHODS FOR THE PROTECTION OF WALL CRESTS AT THE JANOWIEC CASTLE ON THE VISTULA RIVER

Taking technological and economic considerations into account, the available methods selected for the protection of wall crests include capping masonry and roofing (using lead sheet or ceramic fittings). Both methods have already been applied at the site. An additional advantage is the possibility of reusing part of the materials obtained from the dismantling of existing protective structures.

Methods of repair of the wall directly beneath the crest

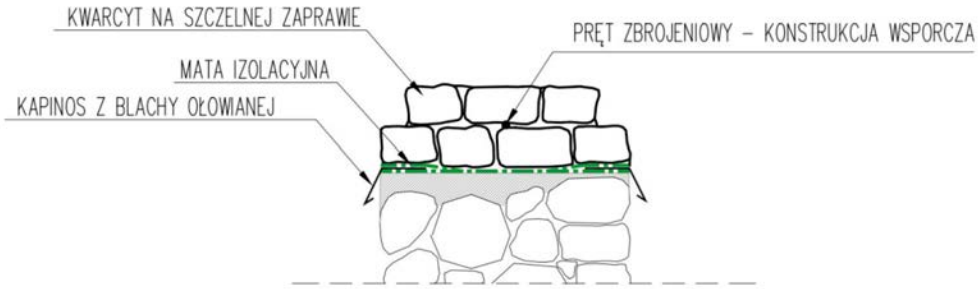
- Rebuilding (repointing and partial masonry replacement) – involves replacing damaged sections of the wall with new masonry. The technology and materials are selected on an individual basis; therefore, a separate technological design must be prepared for each wall section.
- Grouting (injection) – applied to strengthen the wall structure. This method requires the preparation of a detailed design specifying appropriate materials. Drill holes are made in the wall at predetermined spacing, after which the injection material is introduced under pressure. Steel bars are placed in the freshly filled holes in order to monolithise the structure.



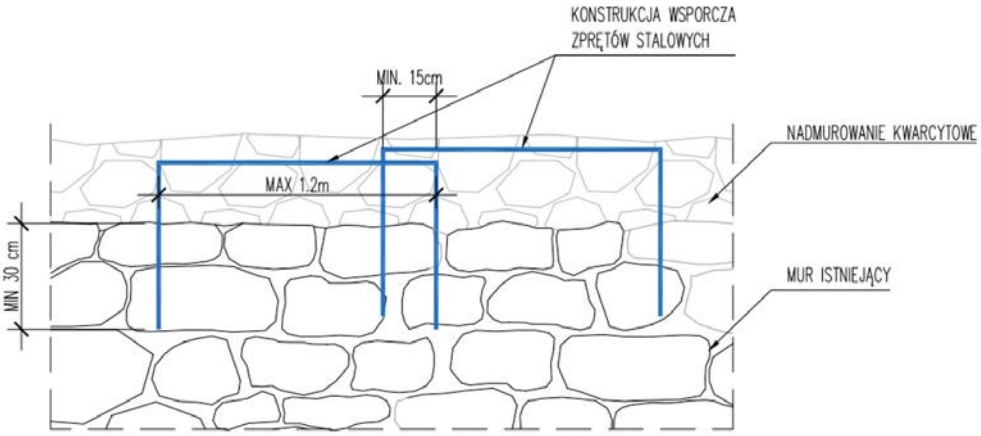
Rys. 5 Diagram of wall repairs beneath the crest. Installation of steel bars within the wall structure following strengthening injection.

Protection of the wall crest by capping masonry

- Quartzite capping with an insulation layer. Due to the deteriorating technical condition of both the existing protection and the wall beneath it, the replacement of damaged sections and the execution of a waterproofing layer limiting water penetration are recommended. The execution of the capping includes the following stages:
  - Dismantling of the existing capping, with the stone retained for reuse.
  - Visual assessment of the technical condition of the wall after exposing the crest.
  - Execution of any necessary strengthening works.
  - Levelling of the surface beneath the insulation using trass mortar and forming drainage slopes.
  - Installation of bentonite mats in accordance with the manufacturer's recommendations.
  - Installation of drip edges made of lead sheet, adjusted to the shape of the wall.
  - Installation of a supporting structure consisting of ribbed steel bars anchored with resin adhesives.
  - Sealing of structural penetrations using bentonite–polymer sealing compounds.
  - Rebuilding the capping with quartzite stone laid in mortar, bonded to the supporting structure, without increasing the height of the wall.



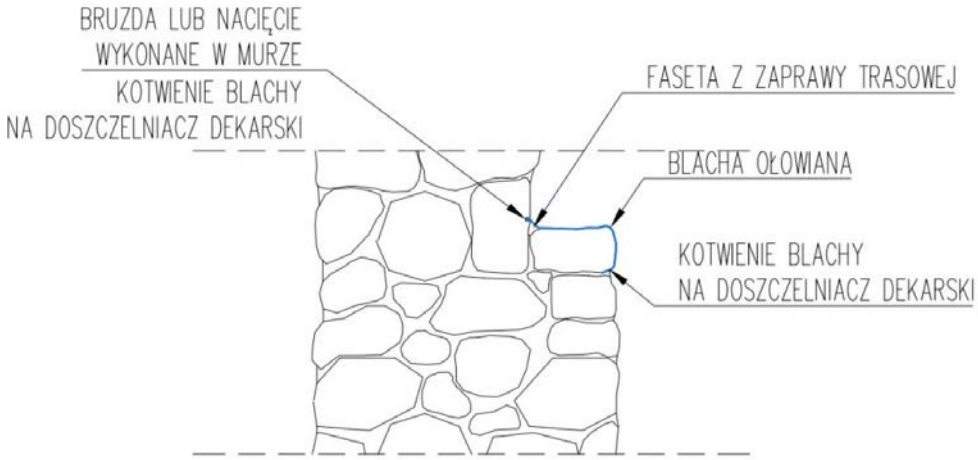
Rys. 6 Cross-section of the wall crest protection with quartzite capping and insulation layer, showing: quartzite laid in tight mortar (kwarcyt na szczelnej zaprawie), insulation mat (mata izolacyjna), lead sheet drip edge (kapinos z blachy ołowianej), reinforcing steel bar – supporting structure (pręt zbrojeniowy – konstrukcja wsporcza).



Rys. 7 Detail of the wall crest protection showing a quartzite capping masonry (nadmurowanie kwarcytowe) fixed to the existing wall (mur istniejący) by means of a steel bar supporting structure (konstrukcja wsporcza z prętów stalowych), with a minimum anchorage length of 15 cm (min. 15 cm), a minimum anchorage depth of 30 cm (min. 30 cm), and a maximum spacing of anchors of 1.2 m (max. 1.2 m)

Protection of wall steps and wall crests

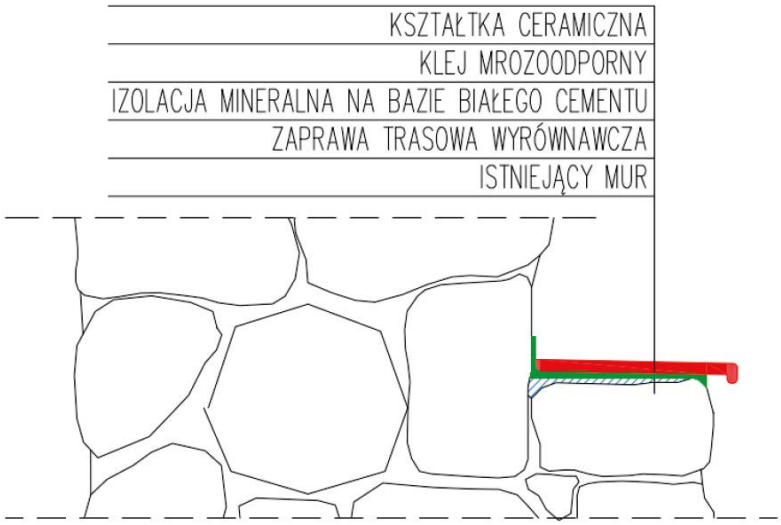
- **Protection using lead sheet.** Lead sheet protects wall steps from the accumulation of water and its penetration into the masonry structure and, due to its plasticity, can be easily adapted to the shape of the wall. The execution procedure includes:
  - Cleaning and assessment of the wall condition.
  - Levelling of the surface with trass mortar and forming a slope of at least 5%.
  - Cutting grooves in the wall above and below the protected section to accommodate the lead sheet.
  - Forming a chamfer (fillet) of trass mortar at the junction of the ledge and the wall.
  - Installation of the lead sheet, anchored in the grooves and with sealed joints.
  - Turning the lower edge of the lead sheet down over one course of stone and hammering it into the mortar joint.



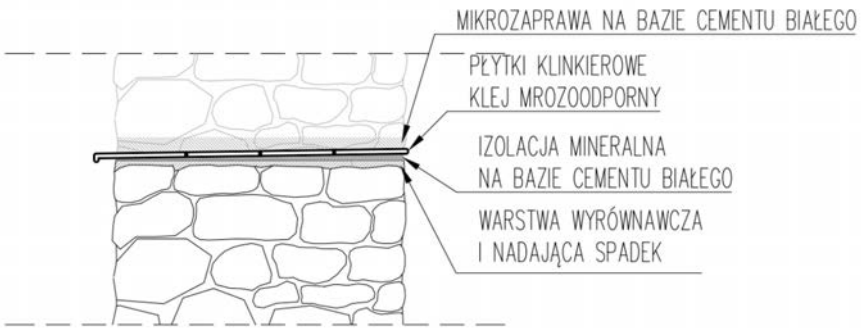
Rys. 8 Detail of wall step protection using a lead sheet (blacha ołowiana) anchored in a groove or cut formed in the masonry (bruzda lub nacięcie wykonane w murze), fixed with roofing sealant (kotwienie blachy na doszczelniacz dekarski), and finished with a chamfer made of trass mortar (faseta z zaprawy trasowej).

Protection using ceramic fittings. Execution technology:

- Assessment of the wall condition and, if necessary, carrying out repairs.
- Levelling of the surface and forming a slope of at least 2% using trass mortar.
- Installation of a mineral insulation layer, also applied to the vertical wall surfaces to a minimum height of 5 cm.
- Installation of frost-resistant ceramic fittings using frost-resistant adhesive, projecting approximately 3 cm beyond the wall face and provided with a profiled drip edge.



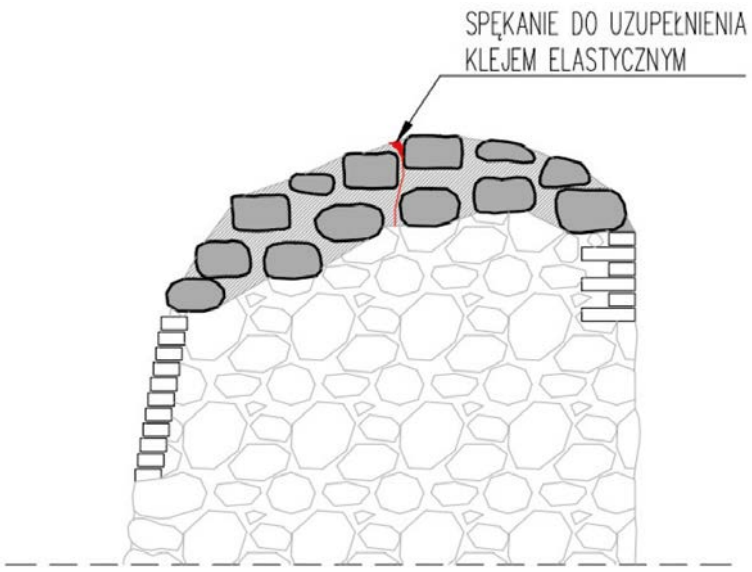
Rys. 9 Detail of wall crest protection using ceramic fittings (kształtka ceramiczna) fixed with frost-resistant adhesive (klej mrozoodporny) on a mineral insulation layer based on white cement (izolacja mineralna na bazie białego cementu), placed on a levelling trass mortar layer (zaprawa trasowa wyrównawcza) applied to the existing wall (istniejący mur)



Rys. 10 Detail of wall crest protection using clinker tiles (płytki klinkierowe) bonded with frost-resistant adhesive (klej mrozoodporny), set on a mineral insulation layer based on white cement (izolacja mineralna na bazie cementu białego), with a levelling and slope-forming layer (warstwa wyrównawcza i nadająca spadek) and finished with a micro-mortar based on white cement (mikrozaprawa na bazie cementu białego)

Repair of existing quartzite protective cappings

- Applied in cases where only the mortar bonding the stone has been damaged and complete dismantling of the capping is unjustified. Cracks are filled with a low-viscosity injection resin, applied by brush impregnation or by gravity pouring, with the process repeated several times.



Rys. 3 Detail of repair of an existing quartzite wall crest capping showing a crack intended to be filled with elastic adhesive (spękanie do uzupełnienia klejem elastycznym) in order to restore continuity and tightness of the protective layer.

6. SUMMARY

In conclusion, the Janowiec Castle remains one of the best-documented examples of permanent ruin conservation in Poland. However, its further preservation requires the implementation of an integrated programme for the protection of wall crests, encompassing both repair works and systematic technical monitoring. Only such an approach can ensure the long-term stabilisation and protection of this exceptional monument, which constitutes an important element of the region's architectural and cultural heritage.

The wall crests of the Janowiec Castle on the Vistula River, as the parts of the structure most exposed to destructive processes, require continuous conservation care. An analysis of historical and contemporary interventions indicates that, despite the intensive protective works carried out between 1976 and 1995 (including the capping of opoka masonry walls, the execution of quartzite wall crests, and structural reinforcements), the current technical condition must be assessed as unsatisfactory.

Material degradation of limestone opoka, loss of mortar, damage caused by freeze–thaw cycles, and biological growth (mosses, lichens, self-seeded vegetation) lead to a reduction in wall cohesion and a loss of structural stability. An additional problem is the lack of an effective system for draining rainwater from the wall crests, which accelerates the processes of deterioration.

A review of available protection methods—from capping and partial rebuilding, through injections and insulation, to roofing structures and the use of ceramic fittings—demonstrates that effective protection requires a comprehensive conservation programme.

Of key importance is the selection of technologies consistent with the principle of minimal intervention and material compatibility, while simultaneously ensuring durability and the legibility of the historic structure.

In the case of the Janowiec Castle, solutions already tested at the site are recommended, such as quartzite capping with insulation and roofing systems (using lead sheet or ceramic fittings). Their advantages include not only technical effectiveness but also the possibility of reusing part of the existing material, which reduces costs and supports the preservation of material authenticity. A crucial improvement is the execution of these protective measures together with the installation of an insulation layer at the interface between the existing wall and the capping masonry. This solution is intended to prevent the penetration of rainwater and meltwater into the interior of the walls..

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PROBLEMATYKA KONSERWCJI I NAPRAW KORON MURÓW ZAMKÓW W JANOWCU NAD WISŁĄ

Streszczenie

Korony murów są najbardziej narażone na destrukcyjne działanie czynników atmosferycznych i biologicznych, co w przypadku zamku w Janowcu, zbudowanego głównie z opoki wapnistej, powoduje przyspieszoną degradację. Autorzy przedstawiają rozwój metod konserwatorskich – od historycznych prób z użyciem darni czy żywic epoksydowych, przez rozwiązania techniczno-biologiczne, po współczesne techniki oparte na nadmurowaniach,

iniekcjach i izolacjach. Opisano historię zamku, od powstania w XVI wieku jako rezydencji Firlejów, przez zniszczenia wojenne i użytkowanie gospodarcze, po działania zabezpieczające prowadzone od lat 70. XX w. Podkreślono znaczenie konserwacji ruin z minimalną ingerencją w oryginalną substancję. Analiza stanu technicznego wykazała poważne uszkodzenia: erozję opoki, ubytki zapraw, korozję biologiczną, uszkodzenia mrozowe i solne, a także negatywne skutki wcześniejszych napraw wykonanych zaprawami cementowymi. Porównanie dokumentacji z lat 2010 i 2025 dowodzi postępującej degradacji oraz wzrostu zagrożeń dla stabilności murów i bezpieczeństwa zwiedzających. W części projektowej zaproponowano kompleksowe rozwiązania: przemurowania i iniekcje wzmacniające, nadmurowania kwarcytowe z izolacją, zabezpieczenia blachą ołowianą i kształtkami ceramicznymi. Rekomendowane są metody sprawdzone już w Janowcu, łączące skuteczność techniczną z zachowaniem autentyzmu i czytelności historycznej struktury. Podsumowując, autorzy wskazują na konieczność wdrożenia zintegrowanego programu konserwatorskiego, obejmującego naprawy, monitoring i systematyczną pielęgnację, aby zapewnić długoterminową ochronę tego wyjątkowego zabytku.

Słowa kluczowe: zamek w Janowcu, korony murów, konserwacja ruin, opoka wapnista, degradacja murów, zabezpieczenia murów, techniki konserwatorskie, architektura obronna, ochrona dziedzictwa, trwała ruina

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TECHNICAL AND CONSERVATION CHALLENGES AT THE DESIGN STAGE OF THE RENOVATION OF THE TIMBER TOWER AND NARTHEX OF THE CHURCH IN WERESZCZYN

The paper presents the course of works related to the comprehensive renovation of the historic timber tower and narthex of the Church of St. Stanislaus, Bishop and Martyr, in Wereszczyn—one of the most valuable examples of wooden sacral architecture in the region. The structure, erected using traditional post-and-beam timber framing, suffered severe damage due to long-term moisture exposure and advanced biological degradation. Based on detailed architectural surveys and mycological investigations, it was determined that the majority of the load-bearing timber elements had lost their mechanical properties and were unsuitable for preservation.

The article describes the process of digital reconstruction of the structure and the execution of structural analyses, which made it possible to better understand the load-bearing behaviour of the entire system. The results confirmed numerous exceedances of permissible deflections and stresses, justifying the necessity of reconstructing the tower and narthex using new materials and elements. The reconstruction design was based on the principle of maximum compliance with the historic spatial layout, supplemented by carefully selected reinforcements and modern timber connectors in order to combine structural safety with respect for the authenticity of the original form.

The paper also addresses the broader conservation context, demonstrating how design decisions take into account both technical requirements and the heritage value of the building. Comparisons with similar projects carried out in Poland and across Europe are presented, highlighting the importance of an interdisciplinary approach to the protection of wooden architectural heritage.

Keywords: timber tower renovation, narthex, post-and-beam timber frame structure, historic buildings, timber conservation, sacral architecture

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1. INTRODUCIOTN

Cultural heritage constitutes a key element of social and historical identity; therefore, its protection and preservation for future generations is a priority for many countries [Mendoza, 2023]. Contemporary research emphasizes that effective and sustainable conservation of historic buildings requires a multidisciplinary approach combining traditional methods with modern technologies [Pachta, 2023]. The dynamic development of digital techniques in recent years has fundamentally transformed heritage conservation practice. Advanced tools such as 3D laser scanning and photogrammetry enable highly accurate and rapid documentation of historic structures [Szostak, 2024].

The resulting 3D models can be integrated with BIM systems, forming so-called H-BIM (Historic Building Information Modeling). This approach allows the centralization of diverse information related to a monument—ranging from point clouds and historical records to current sensor measurements—within a coherent digital model of the building [Escudero, 2023]. Based on such digital models, advanced structural analyses can be carried out using computer-based calculation methods. Moreover, three-dimensional models may also be utilized for additive manufacturing purposes in the future [Kantaros, 2023].

Artificial intelligence and machine learning represent another breakthrough in the field of heritage conservation. Automated analysis of images of historic buildings—using, for example, deep neural networks—enables rapid detection of cracks, material losses, and other forms of degradation on the surfaces of historic structures [Giannuzzi, 2024].

Wooden churches constitute a valuable component of Europe's cultural heritage and require modern technologies and specialized conservation measures to prevent their degradation and potential structural failures [Truong-Hong et al., 2021].

One such structure is the parish church of St. Stanislaus, Bishop and Martyr, in Wereszczyn (Urszulin municipality, Włodawa County, Lublin Voivodeship), whose tower requires urgent renovation. The church was erected in 1634 on the eastern edge of the village of Wereszczyn. It is currently located within a conservation protection zone and is listed in the register of monuments of the Lublin Voivodeship under entry No. A/144. The timber tower above the narthex, which forms the dominant feature of the building's massing, has suffered progressive deterioration due to many years without repairs and now poses a serious risk of structural failure.

This paper presents the results of an assessment of the technical condition of this historic tower and outlines the scope of the planned renovation works. The structure of the article includes the historical and architectural context of the building, the applied methodology of pre-design investigations, a description of the scope and course of the renovation works, and a discussion of the results in relation to European experience in the renovation of historic wooden church towers. The paper concludes with final remarks derived from the conducted analyses.

Fig. 1. View of the church tower and narthex – [photo by A. Kłembokowski]

The church in Wereszczyn is an oriented wooden structure with a simple plan, consisting of a narthex (vestibule), nave, presbytery, and two symmetrical sacristies. Above the narthex, a choir gallery is located, with dimensions of approximately 6.0 × 12.0 m, corresponding to the plan of the narthex below.

A three-storey tower with a square plan is attached to the front (north-eastern) façade of the narthex and aligned with the front wall of the church. The two lower storeys of the tower have base dimensions of approximately 3.76 × 3.74 m and a total height of about 7.3 m, while the third storey (2.82 × 2.82 m, height approx. 3.95 m) is slightly narrower and set back relative to the footprint of the lower storeys [Kłembokowski, technical design, 2024].

The tower is crowned with a four-sided pyramidal roof with a pitch of approximately 70°, incorporating so-called *przypustnice* (stepped transitional roof slopes) inclined at about 45° [Kłembokowski, technical design, 2024]. This architectural form is characteristic of seventeenth-century wooden churches of the Lesser Poland and Lublin regions, combining a simple plan with a prominent front tower serving as both a belfry and a flèche.

Historical records indicate that the church underwent several renovations during the twentieth century. Restoration works were carried out in 1941 and 1964, and in 1975 the original wooden shingle roof covering was replaced with steel sheet roofing. In the 1970s and 1980s, the external cladding (façade boarding) was also replaced, interior walls were finished with wooden panelling, and parts of the floors and ceilings were renewed. However, these interventions were largely limited to the replacement of finishing materials and external sheathing, without comprehensive repair of the tower's load-bearing structure.

The lack of regular conservation maintenance in subsequent decades led to a gradual deterioration of the technical condition of the timber tower structure. At present, the state of preservation of this part of the building is assessed as requiring immediate renovation. Long-term use without ongoing repairs has resulted in advanced degradation of the timber structural elements, particularly in areas most exposed to moisture and biological pest activity.

2. METHODOLOGY – PRE-DESIGN ANALYSES

Prior to commencing the design of the renovation works, comprehensive analyses of the technical condition of the tower and the narthex were carried out. In the first stage, available archival materials were reviewed, including the architectural and conservation inventory of the building. Subsequently, in May 2024, a detailed on-site inspection and visual survey of the structure were conducted, accompanied by photographic documentation and geodetic and construction measurements (including the use of a laser distance meter and a level).

Exploratory openings were made in selected parts of the tower and narthex structure in order to assess the layout and condition of joints concealed beneath cladding layers. A macroscopic assessment of the quality and degree of technical wear of the timber was performed in the exposed areas. In parallel with the visual inspection, mycological and entomological investigations were carried out to evaluate the extent of biological corrosion of the timber caused by fungi, as well as the presence of technical insect pests within the structural elements [Kłembokowski, technical expertise, 2024].

It was found that, as a result of long-term moisture exposure caused by roof leakages, timber elements not protected by preservative treatment had been severely attacked by wood-boring insects. The dominant pest species was identified as the house longhorn beetle (*Hylotrupes bajulus*), with local occurrences of infestation by the common furniture beetle (*Anobium punctatum*). The intensity of fungal attack was lower; no active, extensive fungal infection was observed, although the presence of fungi (e.g. *Serpula lacrymans*) was locally identified at damp interfaces between structural elements.

Fig. 2. Photographs illustrating damage caused by infestation by the house longhorn beetle and the common furniture beetle – [photo by M. Trochonowicz]

The most severe technical deterioration was observed in the floor beams above the narthex (choir), many of which had suffered significant cross-section losses—reaching up to approximately 50%—as a result of decay caused by technical insect pests. The corner posts and diagonal braces of the narthex walls were also heavily affected by biological corrosion and exhibited permanent deformations (out-of-plumb displacements), indicating a substantial loss of structural stiffness.

Fig. 3. Example of a biologically deteriorated floor beam – [photo by M. Trochonowicz]

The subsequent stage involved carrying out computational analyses to verify the load-bearing capacity of the primary structural elements of the tower and the choir. The works related to the structural analysis are described in one of the following sections of the paper.

3. STRUCTURAL ANALYSIS

The works commenced with a detailed survey of the existing structure of the tower and the narthex. Precise geometric measurements were carried out for the entire building volume, as well as for all linear structural elements (posts, beams, braces, etc.) and their traditional carpentry joints.

The previously prepared mycological assessment confirmed the initial concerns: the majority of the timber structural elements had been severely affected by fungal attack and had undergone advanced degradation. The technical condition of many components proved to be so poor that preservation of the original material was no longer feasible. Consequently, dismantling of the structure down to the level of the foundations and its reconstruction using new elements was recommended.

In addition, the measurements revealed that the tower was leaning out of plumb, indicating a loss of its original structural stability. This finding further influenced the decision to dismantle the entire structure and reconstruct it from scratch, restoring its correct geometry and ensuring safe use.

Fig. 4. View of the interior of the tower and narthex – [photo by A. Kłembokowski]

Fig. 5. Photograph taken during measurements of structural element deviations – [photo by A. Kłembokowski]

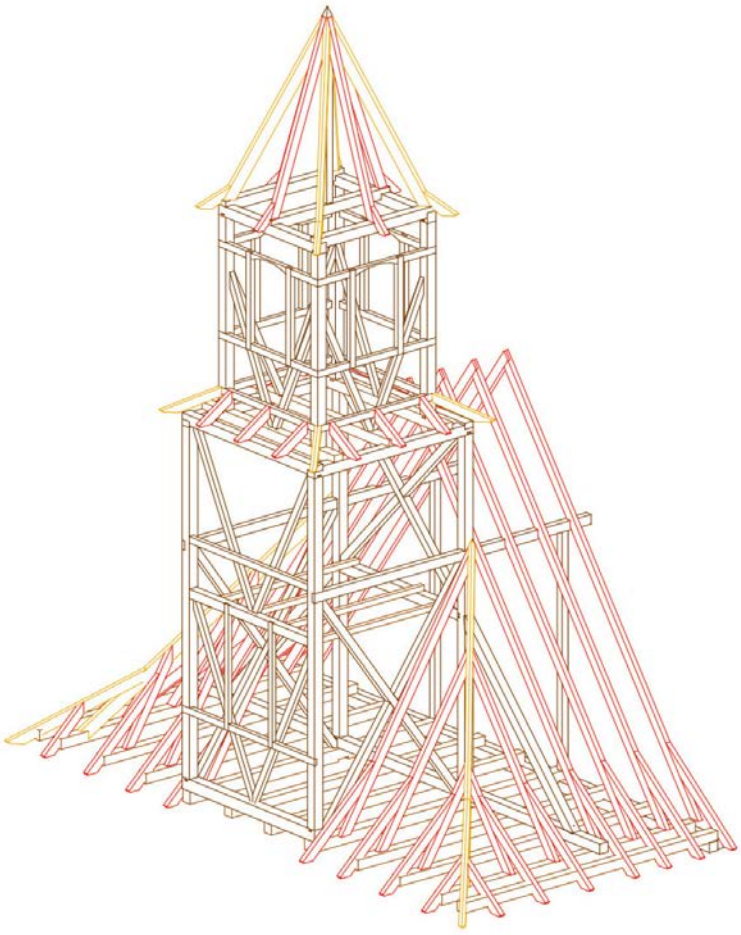

Fig. 6. View of the 3D structural model analysed in the Dietrich's software

A three-dimensional model of the tower and narthex structure was developed based on the survey data. All timber elements and carpentry joints were faithfully reproduced. Using the collected data, a comprehensive 3D model of the entire structure was created in the Dietrich's software environment. Dietrich's supports BIM technology, which means that the H-BIM model developed for analytical purposes may later be expanded and used for other applications beyond structural and strength analysis. This constitutes added value that is particularly important in the context of cultural heritage protection, as discussed in the Introduction.

The structure was divided into transverse and longitudinal systems (with individual walls modelled as frames) and subsequently subjected to spatial calculations in order to assess the global stiffness and load-bearing capacity of the combined tower–narthex structural system.

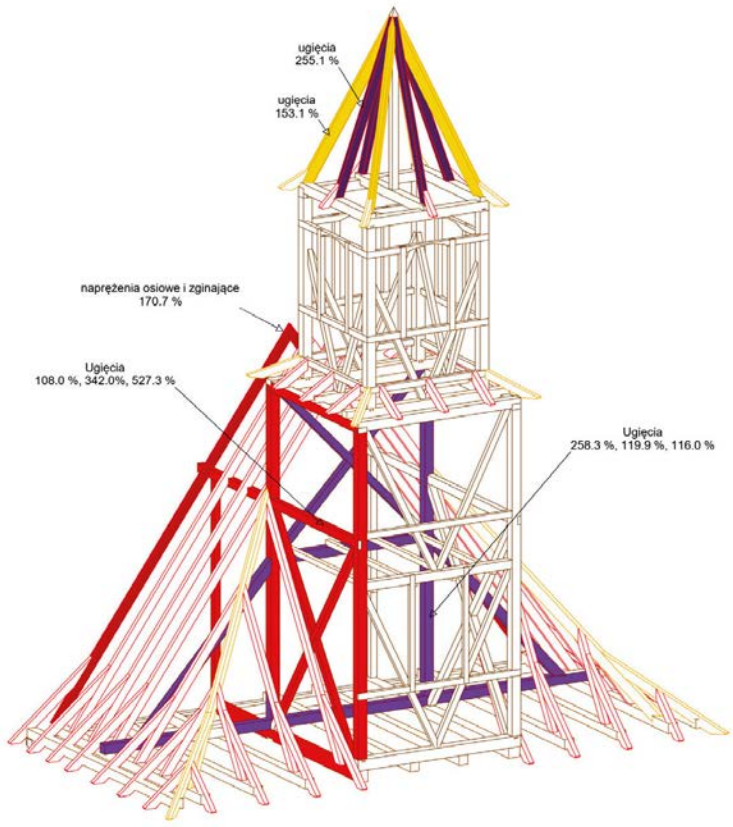

Fig. 7. View of the structural analysis and utilization of elements in the Dietrich's software. The diagram illustrates exceedances of allowable structural parameters, including deflections (ugięcia) and axial and bending stresses (naprężenia osiowe i zginające) in selected structural members.

The conducted structural calculations revealed a number of deficiencies. It was found that, in its current condition, the structure did not meet the requirements of the serviceability limit states (SLS), as deflections of many elements significantly exceeded permissible values (in some locations, calculated deflections were several times higher than the normative limits). Failure to satisfy the ultimate limit states (ULS) was also identified, as stresses resulting from load combinations exceeded the allowable strength of the timber; the maximum calculated utilization reached approximately 170%.

The analysis of joints demonstrated that traditional carpentry connections (e.g. notched joints) were unable to transfer the acting forces in many nodes. In particular, tensile uplift forces occurred that could not be resisted by mortise-and-tenon or notched joints alone. These results confirmed that, without intervention, the

structure would be unstable and unsafe according to contemporary design criteria. This is not surprising given the age of the building: the original builders did not have access to modern calculation methods, and decades of use combined with biological damage had further weakened the original structure.

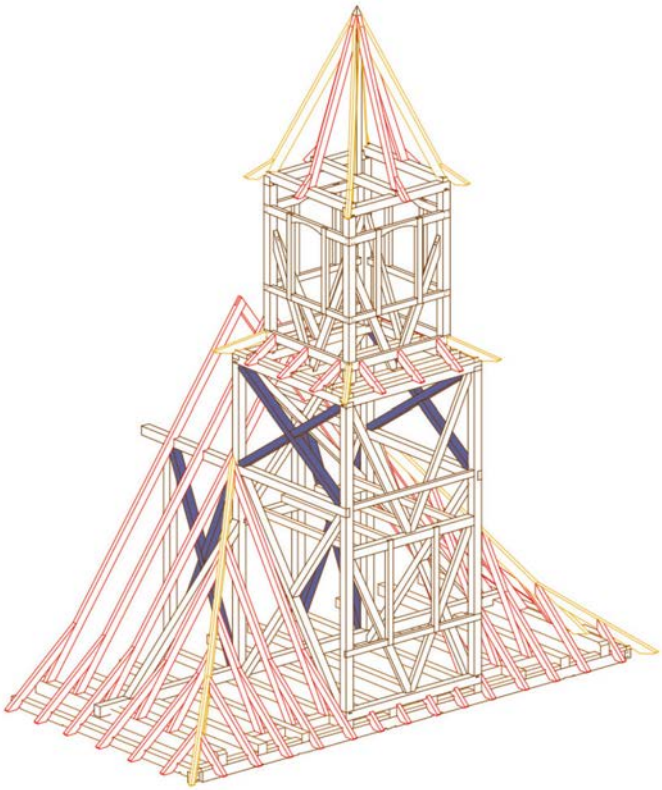

Fig. 8. View of the structure with newly introduced elements in the Dietrich's model

Having gained insight into the actual structural behaviour, the design of the necessary reinforcements was undertaken (marked in dark blue). The guiding principle was to preserve the original structural layout—namely, the transverse frame system of the tower and the longitudinal system of the narthex—in a form as close as possible to the original.

Initially, an attempt was made to reproduce all original solutions without introducing additional elements; however, the calculations showed that the required load-bearing capacity and stiffness could not be achieved without intervention. Therefore, a minimal number of new stiffening elements was introduced. Several missing diagonal braces were added only where absolutely necessary to ensure the spatial stability of the tower and the narthex. After the introduction of these bracings, the structure achieved the required load-bearing parameters. Recalculation confirmed that both

ULS and SLS criteria were now satisfied within normative safety limits. The addition of these braces made it possible to retain the remaining structural layout in its historic character, using elements with dimensions identical to the original ones.

In the subsequent stage, attention was focused on strengthening the joints. The analysis indicated that certain nodes required modification in order to transfer forces that had not been anticipated in the historic carpentry solutions.

In the notched joints connecting posts and beams, uplift forces acting on the elements were identified. Traditional notched joints do not provide resistance to such actions; therefore, discreet fully threaded screws passing through the joints were designed. These steel connectors are concealed within the timber and significantly increase the withdrawal resistance of the joints without altering the appearance of the historic structure.

In designing all secondary elements (additional braces, ties, screws, etc.), materials and techniques compatible with the historic structure were adopted. New timber elements will be made of appropriate wood species and strength classes, while steel connectors were arranged to be as inconspicuous as possible and, where feasible, reversible, allowing for potential future dismantling.

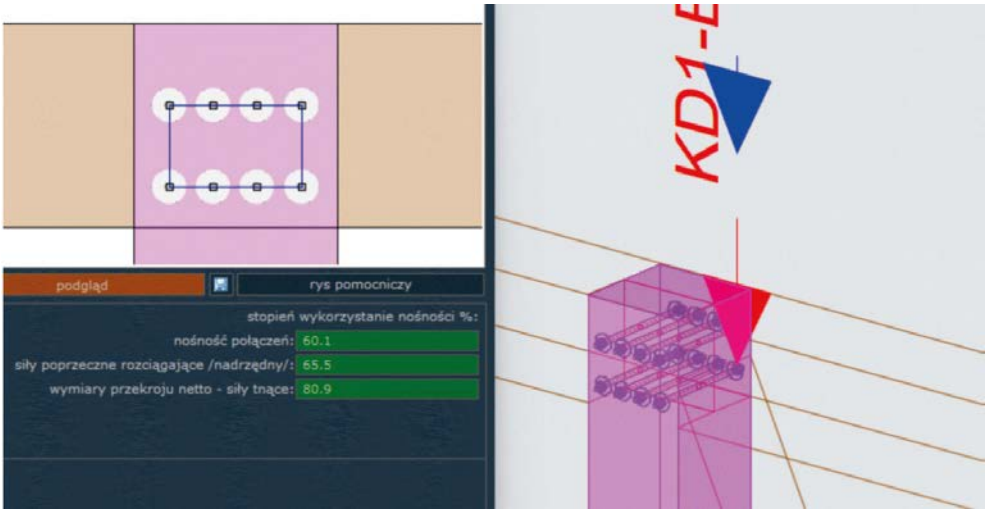

Fig. 9. Widok na analizę połączeń wykonaną w programie Dietrich's. The diagram presents the degree of utilization of connection capacity (stopień wykorzystania nośności połączeń), resultant shear forces (siły poprzeczne rozciągające / nadrzędne), and net cross-section utilization under tensile forces (wymiar przekroju netto – siły tnące).

Due to the extent of the damage, almost the entire structure of the tower and narthex will be reconstructed using new timber elements, while preserving the original dimensions and structural layout. A crucial issue, however, is the integration of the new structure with the remaining original elements of the building.

The church foundations, as well as the adjoining parts of the nave and roof, form the base to which the reconstructed tower and narthex must be connected. New anchorage systems were designed to attach the tower frame to the existing foundations, ensuring full stability and verticality of the structure while correcting the previous inclination.

The interfaces between the new structure and the historic part of the church (the connection between the narthex and the nave wall) were designed to minimize interference with the original fabric. These connections were conceived to transfer loads evenly to the historic material without causing local weakening; for example, bolted connectors were used, which can potentially be removed in the future without damaging the original elements.

As a result of these measures, the new structure cooperates harmoniously with the existing historic fabric, ensuring the required load-bearing capacity and stiffness while respecting the heritage value of the building. All interventions involving the introduction of new elements were carried out with due respect for the historic substance.

4. SUMMARY

The scope and method of renovation of the church tower in Wereszczyn result from the exceptionally poor technical condition of the structure; nevertheless, the adopted approach fits into the broader methodological framework of wooden heritage conservation. The preliminary investigations conducted—ranging from historical research, through detailed surveys using modern measurement techniques and material diagnostics, to structural calculations—are consistent with the recommendations presented in contemporary scientific studies on the protection of historic structures. As indicated by Nuzzo and Faella (2021), effective and sustainable conservation requires a multidisciplinary approach, encompassing in-depth historical studies, detailed measurements, and diagnostic investigations, followed by multi-variant structural analyses prior to design decision-making. This very scheme was applied in Wereszczyn, where decisions regarding the dismantling and reconstruction of the tower were based on reliable expert assessments that took into account both heritage values and current structural design standards.

One of the dilemmas typical of the renovation of historic timber structures is the choice between preserving as much original fabric as possible and ensuring adequate safety for use. The literature emphasizes the overarching principle of minimal intervention, recommending that historic elements be repaired and strengthened rather than replaced, provided this is technically feasible [Nuzzo and Faella, 2021].

In the case of the tower in Wereszczyn, however, the condition of many elements was so critical that there was no realistic possibility of saving them through localized strengthening. The extent of biological corrosion and structural damage

(including column buckling and loss of up to 50% of the cross-section of floor beams) necessitated an almost complete reconstruction of this part of the building in order to ensure safety. It should be noted that similar situations occur in other European countries, where the scale of deterioration requires far-reaching interventions. For example, Kubica et al. (1999) described a case of severe failure of the tower of the pilgrimage church in Piekary Śląskie, where the completely devastated upper part of the masonry tower was reconstructed from scratch, while avoiding the dismantling of the preserved 17 m high timber spire. This unusual solution—leaving the historic spire in place and rebuilding its supporting structure—made it possible to preserve a valuable original crowning element that constituted a symbolic feature of the church.

In Wereszczyn, unfortunately, such a solution was not possible: the entire tower, including its spire, was destroyed, making complete dismantling unavoidable. Nevertheless, the principle of preserving authenticity was reflected in the decision to reincorporate selected, best-preserved fragments of the historic timber structure as historical witnesses. Such an approach is consistent with conservation principles, which advocate preserving original materials wherever possible and avoiding the erasure of the "traces of time" on historic buildings [Nuzzo and Faella, 2021]. As a result, even after comprehensive renovation, the tower will retain elements originating from earlier periods, although they will no longer perform a primary structural function.

In the context of the discussed renovation, it is also worth addressing the issue of preventive maintenance and monitoring of historic structures. The example of the Wereszczyn tower clearly demonstrates that long-term neglect of routine conservation leads to extreme degradation, necessitating costly and invasive interventions. Meanwhile, contemporary research highlights the importance of regular monitoring of historic buildings—particularly tall towers—in order to detect damage and deformations at an early stage.

Thanks to modern technologies such as terrestrial 3D laser scanning, it is possible to periodically monitor deformations and deviations from verticality of church towers with sub-millimetre accuracy. Truong-Hong et al. (2021) described the application of 3D scanning to analyse the geometry of a 500-year-old timber tower of St. Bavo's Church in Haarlem; the study revealed non-uniform wall deformations and allowed for an assessment of the level of structural risk. Such engineering monitoring provides valuable data for planning maintenance activities and can prevent unexpected failures through early intervention.

If a building such as the church in Wereszczyn had been subject to continuous observation and preventive conservation, the scale of degradation could have been significantly reduced—minor roof leakages or the first signs of pest activity could have been detected and addressed before extensive damage to the timber structure occurred. Therefore, the post-renovation programme of regular inspections and protective measures appears essential for extending the service life of the monument.

In conclusion, the renovation of the church tower in Wereszczyn constitutes an interesting case study that combines a classical conservation approach—aimed at preserving authenticity to the greatest possible extent—with the requirements of structural safety. The relevant literature emphasizes that conservation-oriented design should be based on a conscious, scientific approach to historic buildings, integrating historical knowledge, an understanding of traditional construction techniques, and the results of diagnostic investigations and engineering analyses. The Wereszczyn case fully aligns with this paradigm, as the design decisions were made on the basis of interdisciplinary findings developed by specialists from multiple fields.

6. CONCLUSIONS

The analyses carried out and the design measures adopted for the renovation of the historic church tower in Wereszczyn lead to the following conclusions:

- The technical condition of the timber tower prior to renovation was assessed as critical. Long-term lack of repairs, prolonged moisture exposure, and intensive biological corrosion (with a predominance of the house longhorn beetle) had brought the structure to the verge of failure, posing a real risk of structural collapse. This constitutes a clear warning that historic timber buildings require continuous supervision and preventive conservation; otherwise, they are subject to rapid degradation.
- The methodology applied to assess the condition of the structure proved appropriate and effective. A comprehensive investigative approach—including archival research, on-site inspections, exploratory openings, mycological and entomological studies, measurements, and structural calculations—enabled an accurate diagnosis and the development of an adequate repair design. Such interdisciplinary procedures are consistent with best practices in the field of architectural heritage protection.
- The scope of the renovation works had to be extensive due to safety requirements. A decision was made to completely dismantle and reconstruct the tower and the narthex, as partial repair of the existing elements would not have ensured sufficient stability and structural safety. Although this entailed significant intervention in the historic fabric, it was the only viable means of preventing structural failure. Owing to improved technical solutions (e.g. the introduction of additional bracing and strengthened connections), the reconstructed tower will be fully safe and durable.
- Respect for the heritage values of the building was ensured despite the dismantling works. The design предусматривал the preservation and display of selected original structural fragments as historical witnesses. The reconstructed tower will retain the form and architectural details consistent with the seventeenth-century

original, and the use of traditional materials (timber and wooden shingles) will restore its authentic character. In this way, two key objectives have been reconciled: structural safety and historical continuity of the monument.

Finally, it should be emphasized that the execution of the renovation will require continuous specialist supervision. Detailed technical solutions related to the tower structure (e.g. joint reinforcement systems, the species and strength class of the timber used, and assembly techniques) were developed in the detailed design by licensed engineers in cooperation with conservation authorities. This will ensure that the final outcome—beyond its aesthetic qualities—meets all requirements for safety and durability, allowing the historic church in Wereszczyn to serve future generations of worshippers and heritage researchers.

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WYZWANIA TECHNICZNE I KONSERWATORSKIE NA ETAPIE PROJEKTOWYM REMONTU DREWNIANAEJ WIEŻY I BABIŃCA KOŚCIOŁA W WERESCZYNIE

Streszczenie

Publikacja prezentuje przebieg prac związanych z kompleksowym remon-tem zabytkowej wieży i babińca drewnianego kościoła pw. św. Stanisława Biskupa Męczennika w Wereszczynie – jednego z najcenniejszych przykła-dów drewnianej architektury sakralnej regionu. Konstrukcja obiektu, wznie-siona w tradycyjnej technologii słupowo-ryglowej, uległa poważnym uszko-dzeniom na skutek długotrwałego zawilgocenia i zaawansowanej degradacji biologicznej. Na podstawie szczegółowej inwentaryzacji oraz badań mykolo-gicznych ustalono, że większość drewnianych elementów nośnych utraciła swoje właściwości mechaniczne i nie nadaje się do zachowania. W artykule opisano proces cyfrowego odwzorowania konstrukcji w śro-dowisku projektowym Dietrich's oraz wykonania obliczeń statycznych, które pozwoliły lepiej zrozumieć sposób pracy całego układu. Wyniki analiz po-twierdziły liczne przekroczenia dopuszczalnych ugięć i naprężeń, co uzasad-niło konieczność całkowitej rekonstrukcji wieży i babińca z zastosowaniem nowych materiałów. Projekt odtworzeniowy oparto na zasadzie maksymalnej zgodności z historycznym układem przestrzennym, uzupełniając go o staran-nie dobrane wzmocnienia i nowoczesne łączniki ciesielskie – tak, by połączyć bezpieczeństwo konstrukcji z poszanowaniem autentyzmu formy. Artykuł porusza również szerszy kontekst konserwatorski, pokazując, jak decyzje projektowe uwzględniają zarówno wymagania techniczne, jak i war-tość zabytkową obiektu. Przedstawiono także porównania z podobnymi reali-zacjami w Polsce i Europie, wskazując na znaczenie podejścia interdyscypli-narnego w ochronie drewnianego dziedzictwa architektonicznego.

Słowa kluczowe: remont wieży drewnianej, babiniec, konstrukcja słupowo-ryglowa, obiekty zabytkowe, konserwacja drewna, architektura sakralna

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ANALYSIS OF THE DYNAMICS OF CHANGES IN THE FORMATION OF MULTIFAMILY RESIDENTIAL BUILDINGS IN KRAKÓW OVER THE PERIOD 2014-2023

The article includes an analysis of the dynamics of changes in the formation of multifamily residential development in Krakow over the period 2014-2023 in four temporal comparison cycles (years: 2014, 2017, 2020 and 2023). The work is an attempt to answer the questions: (1) What are the dynamics of changes in multifamily residential development in Krakow? (2) What trends and characteristic patterns can be noted in this regard? In order to answer the above, the work proposes the author's method of studying the dynamics of change in the form of a comparison sheet. The sheet is divided into three sections: I. Quantitative data, II. Functional-utility standards. III. Economic standard. For each of the sections, indicators and parameters of multifamily residential development are listed, which are available in publicly available statistical databases provided by the Central Statistical Office (CSO). Thanks to the adopted methodology, the presented tool is universal and can be used to examine the situation regarding multifamily residential development in any city in Poland or in other temporal comparison cycles. The article uses this comparison sheet, examines the current state of affairs regarding the formation of multifamily residential development in Krakow and defines current trends and patterns regarding this issue.

Keywords: multi-family residential development, apartments, real estate market, Krakow

1. INTRODUCTION

The housing deficit in Poland is a social, construction and political challenge that has not been solved since the interwar period until today. This makes the issue of the development of multifamily housing an important, still topical and hotly debated issue. According to reports compiled by both the government and private companies, there is still a significant housing deficit in Poland. Reported figures on the housing gap range from to 650,000 housing units (data behind the 2020 *State of*

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Housing in Poland report) to even approx. 2 million according to PwC's 2022 report *Institutional Tenancy – a lasting trend, not a fad*. The shortage of housing means that multifamily residential development accounts for the vast majority of new construction in Poland, with the largest number of multifamily residential buildings under construction in Poland's largest metropolitan areas. The dynamic development of multifamily residential development in Poland also makes the country's housing market stand out as one of the most rapidly growing in Europe, according to data from the *Living Sector in Poland Built-to-Sell, Private Rented Sector and Student Housing* 2025 *report*. In this context, what are the dynamics of changes in multifamily residential development? Are there any characteristic, noticeable trends noted?

The article attempts to answer the above questions in relation to one of the largest and most dynamically developing metropolises in Poland, the city of Krakow.[2] The issue taken up in the paper is the study of the dynamics of changes in multifamily housing in Krakow over the period 2013-2024. The research hypothesis is the assumption that it is possible to define noticeable trends and patterns regarding the dynamics of changes in multifamily housing in Krakow. In addition, it is assumed that it is possible to create a tool in the form of a comparative spreadsheet, which will make it possible to study changes in multifamily residential development in any city in Poland or in any implementation cycles.

To verify the hypotheses set for the purpose of the article, three main research objectives were defined:

C1. Create a tool to conduct a qualitative study of changes in multifamily housing based on statistical data.

C2. Examine the dynamics of change in multifamily residential development in Krakow using the proposed tool over four comparison cycles (years: 2013, 2017, 2020, and 2023).

C3. Define noticeable trends and patterns regarding changes in multifamily residential development in Krakow.

The results of the study may have applied significance for representatives of local authorities, architects, researchers, as well as people interested in the issues of multifamily housing in Poland. The conclusions presented can serve as useful data for shaping local housing policy, as well as a form of report summarizing the current situation regarding multifamily housing in Krakow. In addition, the proposed research tool in the form of a comparison sheet, thanks to the universal nature of the comparative parameters, can be used to compare the parameters of multifamily housing in other Polish cities in given comparative time cycles, as well as the state of multifamily housing between cities in the same comparative cycles.

The article is divided into five chapters, the Introduction outlines the problem statement, hypotheses and research objectives. Chapter two presents the research

[2] Data behind the 2019 *Report on the State of Polish Metropolises: Kraków City on the Path of Stable Development.*

methodology. Chapter three the proposed research tool. Chapter four contains the results of the research for multifamily residential development in Krakow. Chapter five is a summary, including a discussion and conclusions of the research.

2. METHODOLOGY

In order to achieve the objectives of the study detailed in the introduction of the article, the following research steps were determined:

K1. Identify research methods, tools needed to achieve specific research objectives.

K2. Determine comparative parameters to study changes in multifamily housing. It was assumed that parameters of a universal nature would be used to build the tool from step K4.

K3. Define the time frame of the comparison cycle.

K4. Create a tool to conduct studies of changes in multifamily residential development over specific temporal comparison cycles.

K5. Conduct an analysis of multifamily residential development in Krakow in the given research cycles.

K6. Define noticeable trends and patterns.

K7. Drawing conclusions, validating the hypothesis and possibly deriving further research recommendations.

2.1. Research methods and tools

Diverse research methods were adopted for the study. The variety of methods made it possible to use a wide range of tools to achieve specific goals. (see Table 1)

Tab.1. Summary of research methods and tools used

Research methods and tools		
	Tool	**Target**
A. literature search (printed sources and reliable online sources), subject literature, analytical reports, reports and documents	review and critical analysis of the literature **on the subject**	Examine the current state of knowledge regarding the characteristic parameters of multifamily residential development
	Review and critical analysis of subject literature, reports, reports and documents	Examining the current situation regarding multi-family residential development in Krakow

Research methods and tools		
	Tool	**Target**
B. statistical search (Method of quantitative and statistical research**)** [Niezabitkowska 2014].	analysis of quantitative and statistical data	Collection of quantitative and qualitative data, mainly based on CSO data
C. qualitative research [Niezabitkowska 2014].	comparison sheet	checking the quality and comparative parameters of multifamily residential development in selected temporal comparison cycles in terms of meeting the quality criteria selected for the study
D. analysis and visualization results [Finish 2024].	charts and diagrams	Understanding and accessible presentation of data in a synthesized form to enable conclusions to be drawn
E. logical argumentation	critical assessment (analysis, processing of collected data and its synthesis)	formulation of conclusions

Source.

2.2. Comparative parameters of multi-family residential development

The purpose of the research is to create a research tool for parameters of multifamily residential development, which would allow comparative analysis of multifamily residential development in the adopted temporal cycles of comparison or comparative analysis of the actual state of multifamily residential development between any cities in Poland. So, what parameters of development can be specified, and which of them have a universal character (that is, one that is independent of the conditions of the selected location, or can be compared in selected temporal cycles of comparison for different locations)?

The first step in answering the above question was a literature search on the parameters of multifamily residential development. Based on the existing state of knowledge, the author created a table taking into account the characteristic indicators and parameters of development, listing the elements that make up each indicator. For the methodology adopted, the table also indicates a reference to the systematics proposed in the literature. (See Table 2)

Table 2 Summary of comparative parameters of multi-family residential development

Type param.	Type standard	Indicator/ parameter	Components
URBANISTIC	**AMBIENT STANDARD** [Dabrowska-Milewska 2007].	**Indicators and parameters for relations with the environment** [Dabrowska-Milewska 2007, Bradecki 2021].	Shape of the ensemble in relation to conditions of sunlight, exposure, ventilation
			access to primary services related to the residential function and public services
			Accessibility and transportation, parking and infrastructure conditions
		Indicators and parameters for natural elements [Schneider-Skalska 2004]**.**	relief
			Green/recreational areas, water assumptions
			climate
		Indicators and parameters z related to social space [Schneider-Skalska 2004, Dabrowska-Milewska 2007, Pallado 2016, Bradecki 2021].	territorialism/ability to identify with a **space**
			community group
			urban interiors
			typology of spaces between buildings
			availability of space
		Indicators and parameters for land development [Bradecki 2021]	build-up area
			biologically active areas
			rainwater management
			share of paved areas
		Indicators and parameters for the scale and intensity of multifamily residential development [Dabrowska-Milewska 2007, Bradecki 2021**].**	scale
			building intensity

Type param.	Type standard	Indicator/ parameter	Components
ARCHITECTURAL	STRUCTURE BUILDINGS	**Indicators and parameters for the structure of multi-family residential development** [Pallado 2016, Bradecki 2021].	typology of multifamily residential development due to spatial shape
			Typology of the building due to the formation of vertical communication
			building height/number of floors
			housing typology
	UTILITY STANDARD OF THE BUILDING [Dabrowska-Milewska 2007].	**Indicators and parameters for housing structure**	housing structure
		Indicators and parameters for functional diversity of development	differentiation of functions
		Indicators and parameters for the standard of use of the building [Dabrowska-Milewska 2007].	program and solution of common spaces, general communication zones
			number of apartments per floor/staircase
			Elements that increase the comfort of the building: elevators, garages, storage rooms,
			elements that increase the comfort of the building: balconies/terraces

Type param.	Type standard	Indicator/ parameter	Components
FUNCTIONAL-UTILITY	FUNCTIONAL STANDARD OF THE APARTMENT [Dabrowska-Milewska 2007].	**The parameter of usable area of the apartment**	the size of the usable area of the apartment
		Functional and utility layout parameter [Dabrowska-Milewska 2007].	the way of solving functional and spatial arrangements of the apartment and structure of the premises (including the number of living quarters)
			Sun and light conditions in the apartment
		Indicators for the quality of housing use	ratio of population to dwelling area
			the ratio of the number of residents to the number of rooms in the apartment
COMMUNICATION	PARKING STANDARD	**Indicators and parameters for transportation service** [Bradecki 2021]	The number and location of parking spaces (surface/garage positions)
			number and location of bicycle parking spaces (outdoor spaces/bicycle rooms)
ECONOMIC	ECONOMY STANDARD	**Economic indicators and parameters**	Construction cost per square meter of floor area of housing (PUM)
			Market value of apartments/ average price per sqm PUM
			operating costs
			affordability

Source.

The parameters of multifamily housing were divided into five main types: urban, architectural, functional-utility, transportation and economic.

For the purposes of the article, it is assumed, the division of comparative parameters of multifamily residential development into universal (that is, those that are

general in nature and remain independent of location and local law determinations) and dependent (that is, those that are related to locational conditions, natural conditions, connections with the environment, or result from detailed spatial and architectural and urban planning arrangements under the determinations of local spatial development plans, or decisions on the establishment of development conditions (WZ decisions).

Urban, transportation and some architectural parameters are not taken into account in the further study of the construction of the tool because of the dependence of characteristic urban-architectural parameters and parking standards (such as, among others, building intensity, building area, building height, required ratio of parking spaces) on the provisions of local law or individual decisions of the WZ. Which affects the inextricable link between specific architectural-urban characteristics and a given, specifically defined location, conditions and restrictions arising from the neighborhood of the plot on which the multifamily residential building is located.

Another important aspect for the construction of the comparison tool is the availability of data in the databases of the Central Statistical Office (CSO). The scarcity of data on most architectural features, parameters of the functional-utilitarian layout of apartments and the operating costs of mixing (as a component of economic indicators and parameters) led to the exclusion of these parameters as components of the comparison sheet.

As a result, the indicators and parameters of multifamily residential development in the rest of the study were limited to: the parameter of usable floor area of an apartment, the indicator of the number of living quarters, indicators on the quality of use of an apartment, and economic indicators and parameters.

2.3. Time frame of the comparative cycle

Determination of the length of the comparative cycle. For the purpose of the study, the author assumed that the dynamics of change in the formation of multifamily residential development requires the determination of specific time cycles at intervals longer than the year-to-year comparison periods. It was assumed that the optimal cycle would be to take the period required for actual change in the stock of multifamily residential development. It was assumed that such occurs from the start of construction to the occupancy of the apartment. According to CSO data [CSO 2024], the average duration of construction of multifamily residential buildings in the first three quarters of 2024 was 26.5 months, to which should be added the time needed to obtain an occupancy permit (another 21 days according to the duration of administrative procedures) and the time to finish and settle the apartment. (customarily another two to six months). The above adds up to between 29.5 and 33.5 months. Since most of the statistics needed for the survey are provided by the CSO at annual intervals, the time frame of the comparison cycle has been rounded to three years.

Timeframe for determining comparative cycles. One of the criteria of the study was to show the most up-to-date dynamics of changes in the formation of multifamily housing. However, some of the statistical data needed for this purpose are made available by the CSO in the second half or at the end of the following calendar year relative to the year under study. At the time of compiling the article, not all the data for 2024 was available, hence 2023 was adopted as the closing year of the comparison cycles. This is the last year having the full range of statistical data needed for the study.

For the purpose of the article, four comparison cycles were determined, namely 2023, 2020, 2017 and 2014.

3. TOOL

This chapter presents a proposal for a tool to analyze the facts of multifamily residential development in the form of a comparison sheet. The premise was to create a universal tool that would allow the study of changes in multifamily residential development in any city in Poland or in any comparative cycles using data from CSO statistical databases. Accordingly, in Chapter Two of the article, a selection of comparative parameters of multifamily residential development was carried out to the universal parameters that allow the realization of the research objective set in the work. The parameter of usable floor area of an apartment, the parameter of functional-utility layout in terms of the number of rooms in an apartment, indicators relating to the quality of use of an apartment, and economic indicators and parameters were classified as such. In order to provide a broader spectrum of opportunities to observe changes occurring in the principles of formation and standard of multifamily residential development, the comparative parameters of development were supplemented with quantitative data on the stock of multifamily residential development. The comparison sheet was divided into three sections: I. Quantitative data, II. Functional-utility standard, and III. Economic standard. The proposed survey tool is presented in Table 3.

Section I contains quantitative data on population, number of residential buildings, number of apartments, proportion of housing stock, and data on the number and proportion of building permit decisions for multi-family housing. The tool has been supplemented with quantitative data so as to facilitate observing the dynamics of changes in the formation of multifamily housing in relation to changes in demographics and the city's global resources. The quantitative data allows observing the trend of growth or contraction of the multifamily residential development market in the context of the city's development trends.

Section II contains data on the functional-utility standard, which includes: the size of the floor area of the apartment, the number of rooms in the apartment, floor area per person, and the ratio of the number of people per room in the apartment.

Section III contains tools for studying economic conditions in accordance with the proposed methodology of economic indicators. The CSO database lacks some of

the information on the economic standard, such as the average cost of construction of 1 square meter of floor area of apartments in multifamily housing, or the average operating costs of multifamily housing. Therefore, these parameters were excluded from use in the comparison sheet.

Table 3: Comparison sheet of parameters of multi-family residential development.

Section	Type of indicator/parameter		l.p.	Parameter comparison
I. QUANTITATIVE DATA	**Population**		1.1	number of residents in the city
	Number of residential buildings*		1.2	number of buildings residential in the city
	Number of apartments*		1.3	number of dwellings in city
	Proportion of housing stock in ratio to population (number of residents per dwelling)		1.4	the ratio of the number of inhabitants per 1 dwelling
	Number of construction permits (PnB) obtained for multi-family residential buildings		1.5	number of construction permits obtained for multi-family residential buildings
	Share of construction permits (PnBs) obtained for multifamily residential development in relation to the total number of obtained PnBs and notifications with design for residential buildings.		1.6	Proportion of PnBs for multi-family residential development in relation to total PnBs for residential buildings
II. FUNCTIONAL AND UTILITY STANDARD	**The parameter of usable area of the apartment**	**the size of the usable area of the apartment***	2.1.1	average size of usable area of the apartment – total
			2.1.2	average size of usable area of the apartment – apartments put into use
	Functional and utility layout parameter	**number of rooms in the apartment***	2.2.1	average number of rooms in 1 dwelling – total
			2.2.2	average number of rooms in 1 dwelling- dwellings put into use
	Indicators for quality of use apartments	**floor area per person ***	2.3.	average floor space per person -total
		number of persons per 1 room in the apartment*	2.4	average number of persons per room in a dwelling*

Section	Type of indicator/parameter		l.p.	Parameter comparison
III. ECONOMIC ECONOMIC STANDARD	**Economic indicators and parameters**	**Market value of apartments/ average price per sqm PUM**	3.1.1	Market value of apartments/ average price per sqm of total PUM
			3.1.2	Average price per square meter of PUM on the primary market
			3.1.3	Average price per square meter of PUM on the secondary market
		Financial accessibility (expressed as the ratio of the average gross salary to the average price per square meter of PUM)	3.2.	financial availability of housing
		Financial availability – government support (criterion for occurrence of programs considered to be working and operating on a large scale)	3.3	The presence of government programs to support the purchase of (first) housing

Note: items marked in the table "*" in the CSO databases have statistical data for residential development, with no division into single-family and multi-family housing.

Source.

4. RESULTS OF THE STUDY

The results of the fact-finding survey on multifamily residential development in Krakow from 2014 to 2023 using the proposed tool are presented in Table 4. The following subsections present a summary and synthesis of the survey for each of the three sections: I. Quantitative data, II. Functional-utility standard, III. Economic standard.

Table 4 Results of the study of parameters of multifamily residential development in Krakow in 2014-2023.

Section	Type of indicator/parameter	L.p.	COMPARISON CYCLE			
			2014	2017	2020	2023
I. QUANTITATIVE DATA	**Population** (in thousands of people)	1.1	761,87	767,35	800,53	806,20
	Number of residential buildings*	1.2	47 137*	49 150*	52 980*	56 426*
	Number of apartments*	1.3	353 610*	380 088*	431 775*	458 246*
	Proportion of housing stock (number of residents per housing unit)	1.4	2,15	2,02	1,85	1,76
	Number of construction permits obtained for multi-family residential buildings	1.5	70	157	92	76
	Share of construction permits obtained for multifamily residential development in relation to the total number of obtained PnBs and notifications with design for residential buildings	1.6	13,04%**	21,30%**	15,26%**	13,79%**
II. FUNCTIONAL AND UTILITY STANDARD	**Parameter usable area of the apartment*** average size of usable area of the apartment – total	2.1.1	57,7*	57,7*	57,7*	57,8*
	Parameter usable area of the apartment* average size of the usable area of the apartment – apartments put into use	2.1.2	59,8*	56,1*	58,4*	60,1*
	Functional-utility layout parameter: average number of rooms in 1 dwelling – total*	2.2.1	3,17*	3,13*	3,10*	3,08*
	Functional-utility layout parameter: average number of rooms per dwelling-dwellings put into use *	2.2.2	2,7*	2,6*	2,7*	2,7*
	Indicators for the quality of housing use Average floor space per person -total*.	2.3.1	26,8*	28,6*	31,1*	32,8*
	Indicators on the quality of use of housing *. average number of persons per room in a dwelling*	2.4	0,68*	0,64*	0,60*	0,57*

Section	Type of indicator/parameter	L.p.	COMPARISON CYCLE			
			2014	2017	2020	2023
III. ECONOMIC STANDARD	**Market value of apartments/ average price per 1 sqm of total PUM** (PLN)	3.1.1	6 339	6 497	8 277	11 721
	Average price per 1 m2 of PUM on the primary market (PLN)	3.1.2	6 591	6 582	8 177	11 460
	Average price per 1 m2 of PUM on the secondary market (PLN)	3.1.3	5 764	6 363	8 434	12 062
	Financial accessibility ** (ratio of average gross salary to average price per m^2 of PUM)	3.2.	0,66**	0,76**	0,78**	0,79**
	financial availability- government support- (the criterion for the occurrence of programs considered to be operating and operating on a large scale)	3.3	yes Apartment for the Young (MdM)	yes Apartment for the Young (MdM)	not (non-functional Housing Plus Program)	Yes (First Housing Program, the so-called 2% Safe Credit)

* statistics for residential development, with no division between single-family and multi-family housing.

** own calculations

Source: own compilation based on CSO statistics available on the authority's official website.

4.1. Section I. Quantitative parameters of multifamily residential development in Krakow from 2014 to 2023.

A synthesis of the survey results for Section I. Quantitative data characterizing multifamily residential development in Krakow is presented in Chart 1. The number of dwelling units and apartments shown in the chart is presented collectively for single-family and multifamily residential development due to the availability of data resources in CSO databases. It should be noted that according to CSO statistics, in each research cycle the share of housing units completed in new multi-family buildings in the total number of housing units completed in new residential buildings accounted for 90%. Hence, it can be concluded that despite the lack of separation in the database between single-family and multifamily housing, the graph accurately depicts the dynamics of change in the stock of multifamily housing.

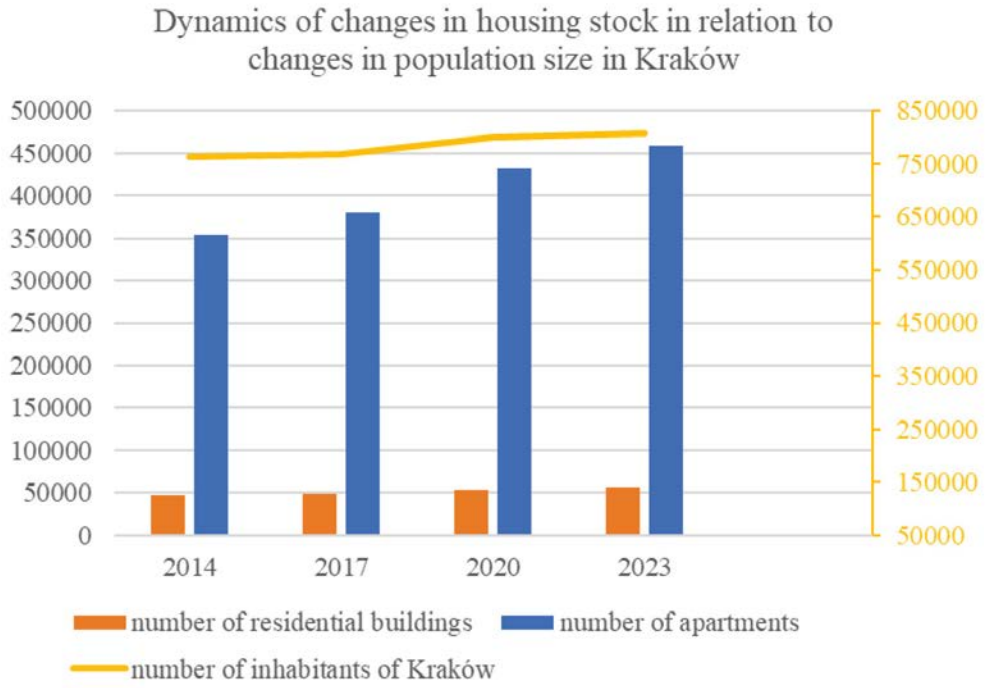

Chart 1. Illustration of the dynamics of changes in the housing stock in relation to changes in the size of the population in Cracow. On the axes in black are marked the scale for the number of apartments and residential buildings, in yellow the scale for the number of people. Values are given in thousands.

Source: own compilation based on CSO statistics available on the authority's official website.

From 2014 to 2023, a steady development of multi-family residential development and an increase in the supply of housing units can be noted. During this period, the increase in the number of residential buildings (an increase in the stock of 9289 buildings) in relation to the increase in the number of housing units (an increase in the stock of 104,636 units) indicates a trend of multi-family residential development with a significant intensity and number of units. This is also indicated by the number of building permit decisions obtained for multifamily housing equal to 395 during the period, as well as the percentage of building permit decisions for multifamily housing in total administrative decisions for residential buildings. (See sections 1.5 and 1.6 of tab.4)

While the increase in the number of housing units over the time period under review is steady, the dynamics of the increase in the number of housing units does not coincide with the dynamics of the increase in Krakow's population, which was strongest between 2017 and 2020. During this period, there was no clearly visible increase in the supply of housing units compared to the other comparative cycles.

The proportions of residents per housing unit have been improving steadily but relatively statically over the time period under review. From 2014 to 2023, the ratios have improved from 2.15 persons per dwelling (2014 data) to 1.76 persons per dwelling (2023 data). (See section 1.4 tab.4)

4.2. Section II. Functional and utilitarian parameters of multifamily residential development in Krakow in 2014-2023.

As in Section I, the data made available in the CSO databases on the functional-use standard of residential development are presented collectively for single-family and multifamily residential development. However, given the reasoning on the share of multifamily residential development presented in Subsection 4.1, these data can be considered to reflect the dynamics of change in the multifamily residential market.

Chart 2 shows changes in the average floor area of apartments collectively for existing and completed apartments (blue) and for completed apartments (orange). The parameter of average floor area taking into account existing and new apartments is characterized by exceptional stability. Over the period 2014-2023, it increased by 0.1 m2 and amounted to 57.8 m2. Larger fluctuations in the average usable area of an apartment can be noted for new apartments put into use during this period. A pattern regarding the decreasing usable area of apartments can be seen between 2014 and 2017. In 2017, the average usable area of an apartment was equal to 56.1 m2. In 2020, there was an increase in the average area to 58.4 m2. The upward trend was also present in 2023. The increase in the usable area of apartments from 2020 should be linked to the design and purchasing trends of apartments as a result of the COVID pandemic in 2019.

During the period under review, there was a systematic increase in the average floor area per capita, moderate in time, which indicates a progressive but not rapid improvement in the quality of life in housing. In 2023, this parameter reached a value of 32.8 m2. Here it is worth comparing this area to the minimum permissible area of an apartment according to current legislation, which is min. 25 m2. The above comparison illustrates a rather favorable pattern of the quality of use of apartments in Krakow.

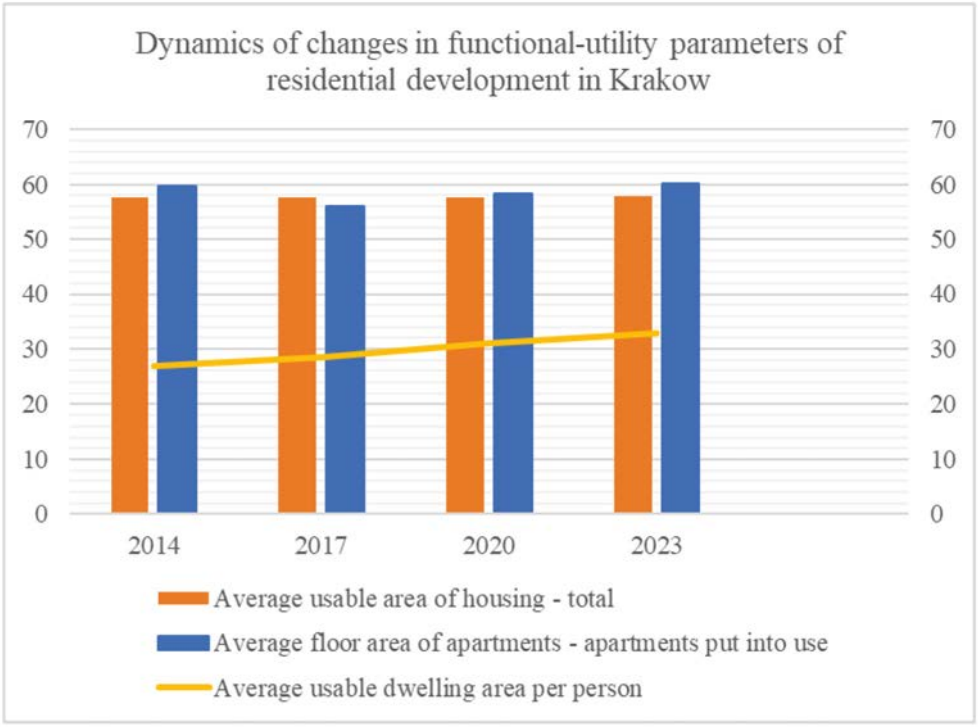

Chart 2. Illustration of the dynamics of changes in the functional-utility parameters of residential development in Krakow. Source: own compilation based on CSO statistics available on the official website of the authority.

Figure 3 shows the relationship of floor area per capita and the dynamics in changes in the average number of rooms in apartments collectively for existing and completed apartments, and separately for new apartments. While, as discussed in the previous paragraph, there have been noticeable changes in the average floor area per capita, the average number of rooms in dwellings put into use has remained remarkably stable. In most of the comparative cycles studied, it was 2.7 rooms per apartment. Analyzing the average number of chambers in existing dwellings and dwellings put into use, a steady trend of decreasing numbers of chambers can be observed. From the comparison of these two parameters, it can be deduced that in the period from 2014 to 2023, significantly smaller apartments were designed as in earlier years.

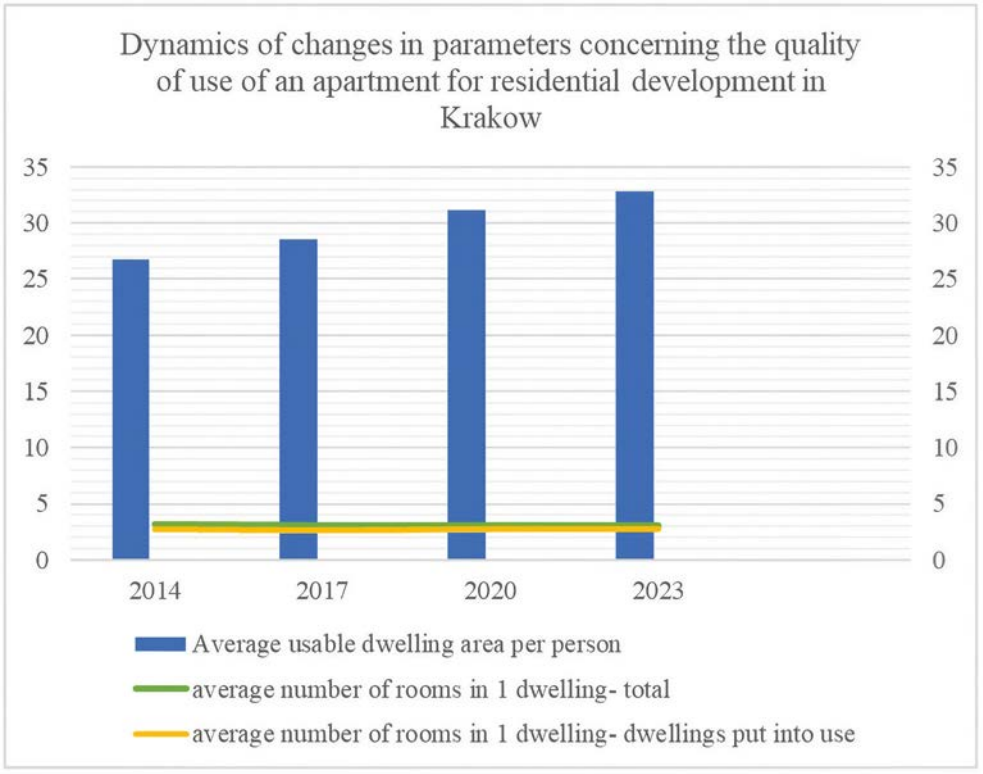

Chart 3. Illustration of the dynamics of changes in parameters concerning the quality of use of a dwelling for residential development in Krakow. Source: own compilation based on CSO statistics available on the official website of the authority.

4.3. Section III. Economic parameters of multifamily residential development in Krakow in 2014-2023.

The economic parameters of the dynamics of changes in multifamily residential development in Krakow are shown in Figure 4. In the period from 2014 to 2023, the average price of 1 m2 of usable floor area (PUM) of an apartment increased to the amount of PLN 11,721, and the price increase compared to 2014 is 184%. The nominal increase in housing prices can be considered highly dynamic. However, when analyzing the price of 1 m2 of PUM in relation to the value of the average gross salary, financial accessibility to housing remains relatively similar in the comparative time cycles assumed in the study. Interestingly, the weakest financial accessibility in this context occurred in 2014, when apartment prices in Krakow were the lowest in the time period studied. At that time, the ratio was 66%, which meant paying 152.65% of the average gross salary for 1 sqm of PUM. By comparison, in 2023, the

ratio was 79%, which was equivalent to having to pay 127.07% of the average gross salary per 1 sqm of PUM.

The second major determinant for the jump in housing prices was government programs to support the purchase of a first home. In 2014 and 2017, housing prices were at a fairly similar level, which can be considered the aftermath of the program "Housing for the Young." The period of the program's operation was from 2014 to 2018. The most significant increase in the price of 1 sq. m. of PUM in the time period under review occurred in 2023, which can be associated with the introduction of another government program, "Program First Apartment, Safe Credit 2%."

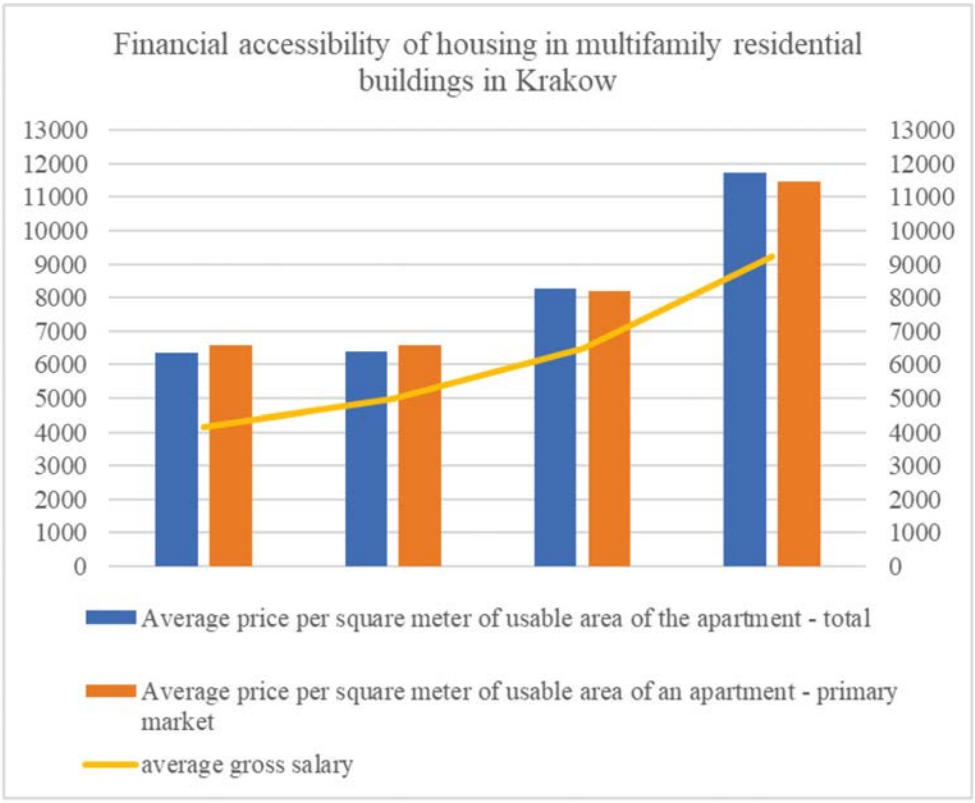

Chart 4. Illustration of the dynamics of financial accessibility to housing in multifamily residential buildings in Krakow in relation to the average price of 1 m2 of PUM and the average gross salary. Source: own compilation based on CSO statistics available on the official website of the authority.

5. SUMMARY

A literature search revealed that numerous studies relating to the analysis of multifamily residential development or its complexes in Krakow can be found in the literature. However, they are mostly in the nature of studies on a specific typology or intensity of development, such as J. Gyurkovich, 2019 (Part 1) and analyses of selected case studies. [Gyurkovich J., 2019 (Part 2); Gyurkovich, M., Gyurkovich, J., 2021] or are comparative analyses of multifamily residential development in Krakow to other cities. [Gyurkovich M., A. Sotoca A., 2019; Bradecki 2021]. For the most part, these analyses refer to parameters or features of development that can be categorized as resulting from local conditions. However, there is quite a small group of studies of a holistic nature, presenting global trends regarding multifamily residential development in Krakow. Here we can mention a study on the preferences of potential buyers of apartments in terms of development parameters. [Adamkiewicz D., Radziszewska-Zielina, E., 2019], an analysis of the typology of multifamily residential development in Poland in 2010-2019, including Krakow examples. [Trębacz P., Mazur R., 2020]. This article fills the gap in terms of a global perspective on conditions related to multifamily residential development in Krakow.

The presented research proved the hypotheses put forward. Based on the results of the research presented in the article, the conclusion arises that the dynamics of changes in the formation of multifamily housing in Krakow is stable and is characterized by a steady development of this typology of housing in the city. As a result, a significant increase in the number of apartments in multifamily residential buildings has been recorded during the period under study. A noticeable pattern is the formation of multi-family residential development of considerable intensity, with a large number of apartments in individual buildings. The continuous development of multifamily housing in Krakow results in an improvement in the quality of housing in the context of increasing usable area of apartments per capita with a constant, fairly small number of rooms per apartment and a relatively fairly stable, low average usable area of apartments.

However, when analyzing data related to the size of usable floor space in relation to the number of people, as well as the number of rooms per capita, it should be taken into account that the statistical data on residents refers to people registered for permanent and temporary residence. Thus, they do not take into account, among others, people renting apartments without registration. This state of affairs can have a significant impact on the formation of the levels of indicators on the size and quality of use of housing, which is a kind of imperfection and limitation for the study of the functional-utility standard of housing on the basis of statistical databases of the Central Statistical Office.

The economic standard of multifamily residential development in Krakow in terms of financial accessibility to housing despite the galloping nominal increase in prices, understood as the ratio of the average gross salary to the price of 1 m2 of

usable floor area of an apartment, remains at a relatively similar level. The financial accessibility of housing in Krakow, as well as globally throughout Poland, is inextricably linked to the trend of significant increases in the price of 1 m2 of usable floor area of an apartment as a result of the introduction or announcement of new government programs to support the purchase of the first apartment.

The article proposed a new tool for studying the actual state of multifamily residential development in Poland in terms of universal parameters, such as functional-utility parameters, as well as quantitative and economic standard. In the conducted research it was proved that the comparison sheet as a research tool allows diagnosing and valorizing the universal parameters and indicators of multifamily residential development. It allows to determine the dynamics of the formation of the economic standard, selected aspects of the functional-utility standard of the development and quantitative data. It would also be recommended to further test the tool on other cities.

In order to obtain as objective a picture as possible of the quality of the residential environment and trends in its formation, the results of the analysis using the comparison sheet should also be juxtaposed with studies of the actual state of affairs regarding the parameters and indicators of multifamily residential development called local in the article, i.e. urban, architectural, and transportation parameters. In the context of Krakow, it is worth noting that while the analysis of multifamily residential development in Krakow based on the universal parameters indicated in the comparison sheet shows a tendency to improve the quality and quantity of multifamily buildings and apartments, quite often the local parameters deteriorate or are shaped at the same level.

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ANALIZA DYNAMIKI ZMIAN W KSZTAŁTOWANIU ZABUDOWY MIESZKALNEJ WIELORODZINNEJ W KRAKOWIE NA PRZESTRZENI LAT 2014-2023

Streszczenie

Artykuł obejmuje analizę dynamiki zmian w kształtowaniu zabudowy mieszkaniowej wielorodzinnej w Krakowie na przestrzeni lat 2014-2023 w czterech czasowych cyklach porównawczych (lata: 2014, 2017, 2020 oraz 2023). Praca jest próbą odpowiedzi na pytania: (1) Jak wygląda dynamika zmian zabudowy mieszkalnej wielorodzinnej w Krakowie? (2) Jakie trendy i charakterystyczne wzorce można odnotować w tym zakresie? Aby odpowiedzieć na powyższe praca proponuje autorską metodę badania dynamiki zmian w formie arkusza porównawczego. Arkusz podzielono na trzy sekcje: I. Dane ilościowe, II. Standard funkcjonalno-użytkowy. III. Standard ekonomiczny. Dla każdej z sekcji wyszczególniono wskaźniki i parametry zabudowy mieszkalnej wielorodzinnej, które dostępne są w ogólnodostępnych bazach danych statystycznych udostępnianych przez Główny Urząd Statystyczny (GUS). Dzięki przyjętej metodologii prezentowane narzędzie ma charakter uniwersalny

i może być wykorzystane do zbadania sytuacji dot. zabudowy mieszkalnej wielorodzinnej w dowolnym mieście w Polsce lub w innych czasowych cyklach porównawczych. W artykule wykorzystano niniejszy arkusz porównawczy, zbadano aktualny stan rzeczy w zakresie kształtowania zabudowy mieszkalnej wielorodzinnej w Krakowie oraz zdefiniowano aktualne tendencje i wzorce dotyczące tego zagadnienia.

Słowa kluczowe: zabudowa mieszkalna wielorodzinna, mieszkania, rynek nieruchomości, Kraków

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THE ENVIRONMENTAL PSYCHOLOGICAL EFFECTS OF FENG SHUI PRINCIPLES: A QUANTITATIVE STUDY BASED ON STUDENT DESIGN PROJECTS

In recent years, both architects and psychologists have become more aware that the way people sense and move through space affects how they feel and think. When looking for ways to describe this connection, many have turned again to ideas found in traditional Feng Shui. Although its origins are ancient, Feng Shui can still be read as a reflection on how human life adapts to the environment rather than as a set of mystical prescriptions. Its central belief—that people and nature work best in balance—links closely to the modern search for physical ease and mental calm. If we place the notion of qi, the living energy discussed in Feng Shui, beside the idea of "perceptual feedback" from environmental psychology, the resemblance is striking [Ulrich 1983]. The present paper explores this relationship by studying six interior design projects completed by students and translating Feng Shui principles into indicators that can be tested and compared in psychological terms.

Keywords: Feng Shui; Environmental Psychology; Psychological Perception; Empirical Case Evaluation

1. INTRODUCTION

Research Background

Most of what people do happens inside buildings or somewhere in between—the house, the street, the park, or the city square. These places don't just provide shelter; they also shape how we think and feel. It has taken a while for architects and psychologists to talk about this in the same language, but the idea that space affects mind has been around for decades. As Gifford [2014] notes,

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environmental psychology looks beyond walls or materials to the way people sense and respond to them. Earlier studies were often limited to numbers—temperature, light, dimensions—while later work began asking what people actually experience when they move through a room. That change of focus turned design itself into a kind of dialogue between person and setting, something alive.

Following this idea, Gibson [1979] and Ulrich [1983] showed that visible or measurable features are only one part of spatial experience; the rest emerges from the subtle interplay between perception and the surrounding environment.

Commonalities Between Feng Shui and Environmental Psychology

Both Feng Shui and environmental psychology explore how spatial qualities influence human comfort and behavior.

In Feng Shui, the idea of "hiding from the wind and gathering qi" reflects an early human sensitivity to environmental comfort—it shows an awareness that gentle, steady airflow and balanced temperature can bring relaxation to both body and mind [Bruun 2003].

Although environmental psychology expresses this understanding in modern scientific terms, it conveys a similar idea: that the coordination of air movement, humidity, and light fosters psychological calm and stability.

Research Objectives and Questions

People generally agree that Feng Shui may have a positive influence on psychological well-being, yet solid empirical evidence is still lacking.

Take the idea of "hiding from the wind and gathering qi." This central concept is often described as a metaphor for balance and harmony of energy, but very few studies have explored how it actually shapes people's emotional or cognitive responses within real spatial settings.

Without measurable data to support these ideas, Feng Shui continues to drift at the margins of modern design science. The present study grows out of this gap. Using six student projects from architecture and interior design courses, it attempts to translate Feng Shui's spatial logic into quantifiable variables that reflect psychological responses.

Article Structure

This article is divided into five main parts: Chapter 1 is the introduction; Part 2 involves theoretical construction, establishing a corresponding analytical framework for Feng Shui and environmental psychology; Part 3 covers the research methodology, describing the methods and evaluation system used; Part 4 presents the research findings, including quantitative analysis data and discussion of relevant cases; Part 5 is the conclusion and outlook, summarizing the main findings and pointing out potential future research directions.

2. THEORETICAL FRAMEWORK

Studying the effects and influences of the environment on human psychology also provides a possible scientific perspective for interpreting Feng Shui principles. Comparing Feng Shui principles with environmental psychology theories reveals a high degree of consistency in their core psychological effects. This consistency makes it possible to establish concrete and verifiable psychological variables for Feng Shui principles.

Table 1. Correspondence between Feng Shui Principles and Environmental Psychology Variables (Author's work)

Feng Shui Principle	**Core Psychological Effect**	**Corresponding Psychological Theory & Concept**	**Spatial Manifestation & Measurable Variables**
Sheltering Wind and Accumulating Qi	Environmental Comfort	Environmental Comfort Theory Stimulation Theory	**Physical Variables:** Airspeed (m/s), Temperature (°C), Relative Humidity (%) **Perceptual Variables:** Airflow Comfort Rating, Spatial Shelter Sense Scale
Backing Mountain Principle	Security Sense of Territory	Defensible Space Theory [Newman, 1972]	**Spatial Variables:** Presence/Absence of solid backing, Rear sightline control range (degrees) **Psychological Variables:** Perceived Safety Scale, Spatial Sense of Territory
Vital Energy (Sheng Qi)	Psychological Restoration Positive Emotion	Biophilia Hypothesis [Wilson, 1984]	**Environmental Variables:** Natural Illuminance (lux), Indoor Plant Coverage Ratio (%), Natural Soundscape Level (dB) **Emotional Variables:** Positive and Negative Affect Schedule (PANAS), Attention Restoration Scale
Bright Hall Openness	Sense of Control Emotional Relaxation	Prospect-Refuge Theory [Appleton, 1975]	**Spatial Variables:** Minimum frontal viewing distance (m), Spatial permeability index **Psychological Variables:** Perceived Control Scale, Profile of Mood States (POMS)
Regular Layout	Sense of Direction Cognitive Fluency	Spatial Legibility [Lynch, 1960]	**Structural Variables:** Spatial plan shape index, Path choice clarity **Cognitive Variables:** Cognitive map accuracy, Wayfinding efficiency

Table 1 takes another look at several core Feng Shui ideas—qi, the idea of balance, and the "mountain-backed" layout—and reads them through the lens of measurable psychological responses.

Rather than staying at the level of theory, the concepts are grounded in data that show how people sense, read, and move through space in practice.

A useful parallel can be seen in Lynch's work on spatial readability (1960), which mirrors the cognitive flow described in Feng Shui; it appears in something as ordinary as how quickly or confidently a person finds direction inside a room.

What this framework really tries to do is to connect Feng Shui principles with environmental psychology and design thinking, keeping the spirit of traditional insight alive while giving it a place in today's design process.

3. RESEARCH METHODOLOGY

The material used in this study came from student coursework in the Interior Design program at the Faculty of Architecture, Poznań University of Technology.

In total, six projects were chosen for review, mostly because they offered enough detail to make comparison possible.

Each student worked on a residential interior and tried to apply a few Feng Shui ideas—sometimes quite intuitively—within a modern context.

Their submissions included drawings, plans, and visual notes that reflected both technical skill and personal interpretation.

Before we began the evaluation, the work was screened once more to make sure that every project included at least some recognizable Feng Shui principles, not just aesthetic imitation.

The evaluation itself was built around five loosely defined psychological variables: visual flow and coherence, protection and safety, access to light and orientation, connection with natural elements, and a general feeling of comfort.

These categories were not rigid; rather, they grew from the overlap between Feng Shui ideas and environmental psychology theory.

Each project was then rated on a five-point scale—from 1 to 5—to reflect how strongly these qualities appeared in the design.

Two reviewers worked independently, following a short guideline document, which helped to reduce personal bias, at least to some extent (see Table 2).

Table 2. Scoring Criteria for Psychological Perception Variables of Design Projects

Evaluation Variable	**1 (Low Degree)**	**5 (High Degree)**	**Basis for Judgment**
Visual Coherence & Flow	Chaotic circulation, numerous visual obstructions	Open, smooth circulation; natural spatial transitions	Floor plan circulation design & perspective visual logic
Protection & Safety Sense	No backing, sightlines exposed	Solid backing for key areas, controllable sightlines in crucial zones	Manifestation of the „Backing Principle" in the design
Light Access & Orientation	Natural light <20%, disorganized orientation	Natural light >60%, rational orientation of main functional areas	Lighting data & orientation markings on floor plans
Biophilic Elements Integration	No natural elements	High integration of plants, water features, etc., with the space	Rendering elements & rationale in design description
Overall Perceived Comfort	Space feels oppressive, no Feng Shui concepts evident	Space feels open and comfortable, good balance of Feng Shui & modern needs	Comprehensive assessment based on prior four indicators & overall design feel

(Author's work)

The scoring was done by two researchers who both had backgrounds in architectural design. They worked separately—each forming their own impressions before comparing results later on.

Once all scores were gathered, the data were summarized and checked through simple statistical averages and deviations. This wasn't just a formal step; it helped to see whether both reviewers were, more or less, consistent in how they judged each project.

4. RESULTS AND DISCUSSION

Quantitative Results

Table 3. Assessment Results by Rater A (Author's work)

Assessment Indicator	Core Principle / EP Rationale	D1	D2	D3	D4	D5	D6	Mean	SD
Visual Coherence & Flow	EP: Legibility & Spatial Clarity; FS: Qi Flow.	4.0	4.0	4.0	3.5	4.0	4.5	4.00	0.37
2. Protection & Safety Space	EP: Territoriality & Safety; FS: Backing Principle.	3.5	4.5	4.0	3.5	3.5	4.0	3.83	0.56
3. Light Access & Orientation	EP: Light Access & Seasonal Affect; FS: Sheng Qi.	4.0	4.0	4.0	3.5	4.0	4.0	3.92	0.38
4. Biophilic Elements Integration	EP: Biophilia Hypothesis; FS: Use of Natural Elements.	3.5	4.0	3.5	4.0	4.5	4.0	3.92	0.49
5. Overall Perceived Comfort	Integrated: Psychological support, Harmony, and Stress reduction.	4.0	4.5	4.0	3.5	4.5	4.0	4.08	0.41
Case Total Score	(Sum of 5 Variables)	19	21	19.5	18	20.5	20.5	19.75	

Table 4. Assessment Results by Rater B (Author's work)

Assessment Indicator	Core Principle / EP Rationale	D1	D2	D3	D4	D5	D6	Mean	SD
1. Visual Coherence & Flow	EP: Legibility & Spatial Clarity; FS: Qi Flow.	3.5	3.5	3.5	2.5	3.5	3.5	3.33	0.37
2. Protection & Safety Space	EP: Territoriality & Safety; FS: Backing Principle.	3.0	4.0	4.5	3.0	4.0	3.5	3.67	0.56
3. Light Access & Orientation	EP: Light Access & Seasonal Affect; FS: Sheng Qi.	4.0	4.5	4.5	3.5	4.0	4.0	4.08	0.38

Assessment Indicator	Core Principle / EP Rationale	D1	D2	D3	D4	D5	D6	Mean	SD
4. Biophilic Elements Integration	EP: Biophilia Hypothesis; FS: Use of Natural Elements.	4.5	4.5	4.0	3.5	4.5	3.5	4.08	0.49
5. Overall Perceived Comfort	Integrated: Psychological support, Harmony, and Stress reduction.	4.0	4.5	4.5	3.5	4.5	4.5	4.25	0.41
Case Total Score	(Sum of 5 Variables)	19	21	21	16	20.5	19	19.42	

Table 5. Final Assessment Results (Author's work)

Assessment Indicator	Core Principle / EP Rationale	Rater A Mean	Rater B Mean	Final Mean(M)	Standard Deviation (SD)
Visual Coherence & Flow	EP: Legibility & Spatial Clarity; FS: Qi Flow.	4.0	3.33	3.67	0.49
2. Protection & Safety Space	EP: Territoriality & Safety; FS: Backing Principle.	3.83	3.67	3.75	0.41
Light Access & Orientation	EP: Light Access & Seasonal Affect; FS: Sheng Qi.	3.92	4.08	4.00	0.25
4. Biophilic Elements Integration	EP: Biophilia Hypothesis; FS: Use of Natural Elements.	3.92	4.08	4.00	0.47
5. Overall Perceived Comfort	Integrated: Psychological support, Harmony, and Stress reduction.	4.08	4.25	4.17	0.41
Case Total Score	(Sum of 5 Variables)	19.75	19.42	19.59	1.36

Note: FS = Feng Shui. All ratings are based on a 5-point Likert scale. ICC = Intraclass Correlation Coefficient.

When we looked again at the results (Table 5), the pattern felt stable. The two sets of scores were close—Rater A gave an overall mean of 19.75 and Rater B 19.42. A combined average of 19.59 suggests that, despite small personal differences, both

followed a similar line of thinking. It's fair to say the process held together well and the results can be trusted.

Among the indicators, Light Access & Orientation and Biophilic Elements Integration stood out—both reaching 4.00 on average. The light-related variable also showed the least spread (SD = 0.25), which, to me, suggests that natural light and greenery almost always lifted the emotional tone of a space. That's in line with Wilson's (1984) biophilia idea and, interestingly, echoes the Feng Shui notion of "life energy."

Spaces that gave a stronger sense of protection averaged 3.75, linking ideas of safety from environmental psychology with the Feng Shui "support" principle. Meanwhile, Visual Coherence and Fluency came out lower at 3.67 (SD = 0.49). It seems that while circulation paths were generally logical, many rooms lacked the smoother transitions that make movement feel natural.

Finally, Overall Perceived Comfort reached 4.17, the highest score across all categories. Even though a few layouts were imperfect, most still conveyed balance and calm—a sign, perhaps, that traditional Feng Shui ideas can quietly shape modern design when translated into measurable terms.

Case Discussion

Project 2 was chosen for a closer look because, in many ways, it captured the idea of design translation that this study aimed to explore. It scored 21 points in total—not the highest mark, though high enough to make its details worth discussing. At first glance the design appears quite ordinary, yet several Feng Shui principles quietly shape the way the space works. The shared areas are arranged so that air drifts easily from one room to another, avoiding that heavy, stagnant feeling that closed interiors sometimes have. Natural wood tones, used as the main color, lend a soft warmth and make the atmosphere feel calm rather than rigid. Wide windows open toward the garden, letting daylight and greenery spill inside; the interior and exterior seem to breathe together.

In the end, the space feels balanced—functional but still emotional, rational yet comfortable. It's hard to tell whether that balance was planned deliberately or simply felt by intuition, but either way it reflects the quiet harmony that lies at the heart of Feng Shui.

Figure 1. Floor plan and visualizations of Project 2

5. CONCLUSION

In this study, Feng Shui was explored not as a belief but as a way to read how people sense space. We tried to see, in a measurable way, how ideas such as flow, light, or orientation might shape comfort and attention. That observation, small as it is, hints that ancient design logic still speaks to modern psychology. What began as a cultural idea may, in fact, describe how the human mind reacts to spatial cues. Looking ahead, testing this approach in lived environments, or even with tools that track the body's responses, could tell us more about how harmony in space affects well-being over time.

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PSYCHOLOGICZNE EFEKTY ŚRODOWISKOWE ZASAD FENG SHUI: BADANIE ILOŚCIOWE OPARTE NA PROJEKTACH STUDENCKICH

Streszczenie

W ostatnich latach zarówno architekci, jak i psychologowie coraz bardziej dostrzegają, że sposób, w jaki ludzie postrzegają przestrzeń i poruszają się w niej, wpływa na ich emocje i sposób myślenia. Szukając sposobów opisu tego związku, wielu badaczy ponownie zwraca się ku ideom obecnym w tradycyjnym Feng Shui. Choć jego korzenie sięgają starożytności, Feng Shui można dziś odczytywać raczej jako refleksję nad tym, jak ludzkie życie dostosowuje się do otoczenia, niż jako zbiór mistycznych nakazów. Jego centralne założenie – że człowiek i natura funkcjonują najlepiej w stanie równowagi – pozostaje blisko związane ze współczesnym dążeniem do fizycznego komfortu i psychicznego spokoju. Jeśli zestawić pojęcie qi, życiowej energii opisywanej w Feng Shui, z koncepcją „sprzężenia percepcyjnego" znaną z psychologii środowiskowej, podobieństwo okazuje się uderzające [Ulrich 1983]. Niniejszy artykuł bada tę relację, analizując sześć projektów wnętrz wykonanych przez studentów oraz przekładając zasady Feng Shui na wskaźniki, które można testować i porównywać w kategoriach psychologicznych.

Słowa kluczowe: Feng Shui; Psychologia środowiskowa; Percepcja psychologiczna; Empiryczna ocena przypadków

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A PATTERN LANGUAGE FOR CINEMA: SPATIAL SEMIOTICS IN VILLENEUVE'S DUNE

The article explores the possibility of applying Christopher Alexander's Pattern Language to the analysis of film architecture, using Denis Villeneuve's Dune (2021) as a case study. The research examines whether architectural patterns can function as a visual language that conveys relationships, hierarchies, and power dynamics within cinematic storytelling. Through diagrammatic mapping of Alexander's patterns across three scales—city, building, and construction—the study identifies their recurrence within Dune's narrative structure. The findings suggest that architecture in the film acts not merely as decor but as a semiotic and narrative agent, shaping the viewer's perception of space, emotion, and ideology. By linking spatial design with interpersonal and political relationships, the film's built environment becomes an expressive system that supports storytelling. The study concludes that Alexander's framework offers a valuable analytical tool for interpreting cinematic world-building and suggests directions for further research across other science fiction films to assess the universality of this approach.

Keywords: film architecture, Pattern Language, psychology of architecture, relations, cinematic space, visual storytelling, science fiction cinema, Dune (2021)

1. INTRODUCTION, DEFINING THE RESEARCH PROBLEM

Christopher Alexander and his team in his book "The Language of Patterns" [Alexander, Ishikawa, and Silverstein 1977] wrote down archetypes that are encoded in the human psyche, patterns that already exist in consciousness – we perceive architecture emotionally [Lenartowicz 1992; 2010]. He also gave his proposed urban, architectural and interior design solutions to some social problems. The patterns are concerned with shaping urbanism (regions, cities, neighborhoods, settlements, relations between them), buildings, interiors and structures. Its patterns are intended to build good relations between people through architecture. In addition, these patterns offer a unique lens through which we can understand the interplay between built environments and human behavior, suggesting that architecture is not merely a physical construct but also a cultural narrative device.

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Architecture appears in virtually every film as a backdrop to the events unfolding. It is inherent in cinematography because it accompanies people in real life, including in experiencing emotions. Which is already used in a conscious manner in films [Chung 2024]. This omnipresence of architecture in films underscores its dual role as both a visual element and a carrier of symbolic meaning that can shape and reflect societal values. Research by Skoczylas [Skoczylas 2024] shows that film architecture, through the use of universal patterns, becomes a carrier of collective memory, which supports the thesis of the deeper importance of space in shaping social relationships. Kuhn [Kuhn 1999] notes that science fiction cinema has long relied on architectural space as a metaphor for power, control, and otherness, making it a critical site for ideological analysis. According to Christopher Alexander's thesis, these patterns are rooted in the human psyche and influence our emotional perception of space, which in a film setting allows viewers to identify with universal cultural archetypes. This approach emphasizes that architecture in film is not just a backdrop for the action, but actively participates in the construction of collective cultural memory and the formation of social relations. The repetition of patterns in many films, serving to portray similar emotions or relationships, points to the possibility of creating a catalog of film architecture archetype patterns or at least a partial use of Alexander's "Pattern Language". The potential of patterns as a tool for designing film spaces that appeal to universal values and experiences is pointed out.

Cinematic architecture is additionally more interesting, from the point of view of the article, when it is created specifically for a particular film. Utility, good layout of functions in a building or durability are not so important when building a set for a scene or frame. Its lifespan is very short, temporary, so its appearance, may be the result of what we want to portray in the scene [Bordwell 1985]. By focusing on the transient and highly stylized nature of film sets, we can explore how temporary architectural designs are imbued with enduring cultural and emotional resonances.

In movies, filmmakers don't always care about showing good relationships between people, but this pool of relationships is very wide (including intimate relationships, friendship, neutrality, formal relationships, showing power, hostility, rivalry, loneliness) – including in the film Dune itself [Hamnu 2024; Winston 2020]. Such a diversity of interpersonal dynamics demands that the cinematic space itself be versatile, capable of mirroring the multifaceted nature of human connections. The use of specific architectural elements to highlight certain emotional tones or narrative threads further enriches the viewer's engagement with the film's world.

The research asks whether the architecture in Dune functions not merely as scenic decor, but as a structured visual language that articulates relationships, hierarchies, and power dynamics across multiple narrative levels. Can Alexander's patterns operate as archetypal, semiotically charged forms in the context of speculative cinema? If so, might they serve as a visual grammar that enhances narrative coherence and emotional resonance? This case study uses diagrammatic mapping of architectural patterns and relational structures within Dune to test this hypothesis.

By foregrounding architecture as a narratively functional system, this study contributes to growing interdisciplinary dialogues between film studies, design theory, and spatial semiotics. It also raises a broader methodological question: can architectural pattern languages offer new analytical frameworks for understanding the visual logic of world-building in science fiction cinema?

2. SELECTION OF FILM FOR RESEARCH – DUNE

To test the validity of this concept, I chose a film that meets the following conditions:

- it is in the science-fiction or fantasy genre
- its production was after the publication of Alexander's book (after 1977)
- the place of action takes place on a planet (not in space on a ship) and resembles conditions on Earth (people can go outside from buildings in a free way, without imposing anything more on themselves than if they left their homes on Earth)
- its audience includes people from many cultural backgrounds
- it is appreciated in the film community for its setting

These conditions are met, among others, by the 2021 film Dune from Legendary Pictures / Warner Bros studio [Villeneuve 2021]. he film's production design has been awarded, among other prizes, by the Scenographers Guild of America in 2022 for best production design in a fantasy film, a BAFTA award and an Academy Award (also in 2022) [Filmweb 2024a; 2024b]. The accolades received by Dune underscore its significant contribution to the field of film production design, highlighting how architecture and set design are integral to the storytelling process.

The choice of Dune as a subject of research is also grounded in the immense influence that the film has had on modern cinematic architecture. Its groundbreaking approach to production design not only reflects the narrative of the film but also helps to convey its philosophical and political undercurrents, making it a suitable case study for this analysis.

Denis Villeneuve (director and writer), Patrice Vermette (production designer) were responsible for creating the film vision of Arrakis, the city of Arrakeen and its architecture. Villeneuve's approach to the film was one of highly stylized realism, aiming to create a world that felt both timeless and grounded in the physical laws of nature, despite its fantastical setting. They wanted to reflect the plot through architecture [Conklin 2024; Koç 2024]. The creative team used a mix of real-world references, futuristic elements, and symbolic design principles to imbue the sets with cultural and political meaning. The architecture of Arrakeen, for example, is not just a physical structure but a tool for conveying the complex relationships between power, colonialism, and resistance, which are central to the film's narrative.

The film Dune and the world created for it is an adaptation of Frank Herbert's 1965 book. In the article I will deal only with the film version, I will omit the description

from the book for the sake of clarity of the article. While the novel is a cornerstone of science fiction literature, the film's visual interpretation offers a new layer of meaning, particularly in how the environment and architecture serve as metaphors for the larger themes of the story. Describing all the architecture present in the film, and analyzing it, is a very broad topic, so I have chosen one area for research.

In this article, I will focus on exploring the patterns used to build the architecture of the governor's palace (the Arrakeen Residency) and the city of Arrakeen in order to illustrate the characteristics of the relationship between the Fremen (indigenous people) and the Emperor represented by the ruling family on the planet (the colonizers, the Harkonnen family and the Atreides family). The architecture of Arrakeen was designed to reflect the social dynamics between these groups, with the grandeur and coolness of the Harkonnen structures standing in stark contrast to the more humble and inscribed environmental spaces of the Fremen. An extended description of the accounts showing anti-colonial attitudes in Diune is included in Zrníková's thesis [Zrníková 2024]. The architecture becomes a silent yet powerful player in this political drama, shaping how the characters move through space and how they interact with each other and their environment.

A deeper exploration of the colonial aspects of the film can be drawn through the architectural choices made by the production designers. The imposing, brutalist structures of the Harkonnen family exemplify the oppressive power dynamics at play, while the organic, flowing design elements associated with the Fremen reflect their resistance and adaptability.

I will look at this using the scale proposed by Alexander and according to his understanding of these designations:

- towns scale
- scale of the buildings
- scale of the constructions

It is impossible to give all the patterns covered in the book that the creators used (in one article), so this will be a subjective selection of those that most shape a given space while telling a story. This selection focuses on key elements that play a direct role in the portrayal of the political and social tension within the narrative, offering a focused lens through which to examine how architecture, even in a science fiction setting, can serve as a powerful storytelling tool.

3. DESCRIPTION OF THE CITY AND THE ARRAKEEN RESIDENCY

3.1. Towns

The planet on which the city of Arrakeen is built is a desert planet. It is characterized by a harsh and unforgiving desert environment. The view of the planet from space shows nothing but the color of sand. There are no patches of

vegetation or water on its surface. The water is confined inside the planet. In this desert world there is a valuable spice that the colonizers (a family chosen by the Emperor who rules the entire universe) extract. However, due to the lack of water, it is the most valuable resource. [Dune Wiki, 2024; Villeneuve, 2021 Hilburg, 2021]

The city of Arrakeen is built on and surrounded by rocks. The rocks form a barrier against threats from nature and the Fremens, the indigenous people. The wall completes the places where the lack of continuity of the rocks does not create a safe barrier. The rocks primarily protect cities from attack by maggots – huge desert animals that are a threat to humans. Places where rocks are absent are practically inaccessible for development. The planet cannot be surrendered to itself, but it is possible to cooperate with it, as evidenced by the Fremen sichs, however, this is not the subject of this article.

Buildings in the city are built very close to each other. In fact, it is hard to see the spaces between them. The buildings have no unnecessary openings. They are of similar height with irregularly occurring towers throughout the city. The massiveness of the city, with its dense urban fabric, creates a sense of permanence, making it clear that the city is both a place of habitation and defense. The lack of openings in the walls of buildings, coupled with the geometric shapes, evokes a sense of utility and functionality rather than comfort. The architecture is minimalist, with an emphasis on stability and security rather than ornamentation.

The governor's residence towers over the city. The seat of power still has representative, military, residential functions. The palace is the largest building in the city by volume, and is the tallest and most extensive (but lower than the surrounding rocks). Its proportions are designed to overwhelm the viewer, showcasing the scale of the empire's dominance over the planet. The architecture of the palace reflects its dual role as both a place of power and a military stronghold. Its form is imposing, with long, horizontal lines and heavy, angular shapes. The materials used for the construction are raw and solid, enhancing the brutalist aesthetic. The palace's bulkiness contrasts sharply with the surrounding city. Its terraces and flat roof offer panoramic views of the surrounding desert.

3.2. Buildings

In the Arrakeen residence one can see inspiration from brutalism [Li 2022], Mayan architecture, Egyptian pyramids, Vilanova Artigas or Frank Lloyd Wright designs. The shape of the building resembles a zikkurat. It is shaped vertically, with horizontal planes of roofs – terraces. On one of them 20 trees are planted.

The verticality of the building was achieved through stepped layers, as in the ziggurat, but primarily through the use of vertical, narrow and regular slits in the façade and vertical "razor blades" protruding from the façade of different heights, arranged increasing towards the building's centerline.

The palace is built of simple geometric forms, with walls sloping towards the center of the building. Narrow slots for windows are planned only where needed, often without direct opportunity to infest the world, but only to illuminate the interior.

3.3. Constructions

The material used to construct the building is concrete. It can be seen both outside and inside the palace. The concrete surfaces are raw and textured, giving a sense of unfinished solidity.

The interiors of the mansion are illuminated by light coming in through small openings, mostly without a direct view of the outside. However, the main areas are well lit. Spaces that do not need it are left in semi-darkness.

There are at least two bas-reliefs in the palace. The walls show traces of planking forming mostly straight horizontal lines. The bas-reliefs, along with the textural walls, add a sense of history and gravitas to the interior of the palace, suggesting a connection to ancient traditions and a continuous legacy of power. The interiors are austere with minimal furniture. The sparse, functional furniture adds to the feeling of coldness and isolation within the building, reinforcing the idea that this is a space meant for work and governance rather than comfort. The lack of decoration emphasizes the utilitarian purpose of the space, where every element serves a function, from the placement of windows to the arrangement of furniture.

Tab.1 provides a brief summary of these descriptions.

Tab. 1. Summary of the architectural and urban features of Arrakeen

TOWNS	**BUILDINGS**	**CONSTRUCTIONS**
– Desert world – City built on rocks – Places between rocks enclosed by a wall – Buildings in the city are compact – The largest building – the governor's palace	– Zikkurat – Brutalism – Vertical shaped – Dominating the surrounding buildings – "Submitting" to the dominance of rocks – Simple, geometric forms – Narrow window slots – Purpose of building – bunker, protection, fortress – military and against nature; seat of ruler – showing prestige, hierarchy.	– Strictness – Inside and outside the same material – Small number of windows giving a view – Shaping the space with light – Concrete – Reliefs

Source: own study

Reading the descriptions of the created world, the city and the building, one can expect the architecture to show the following relationships:

- indigenous people – colonizers
- colonizer – emperor
- nature – built world
- the family managing the planet – the previous administrator.

In order to structure the above-mentioned relationships, they were divided into three levels (relationship levels). This levels are not the same as the scales given by Alexander, although some correlations can be noted.

- macro level- relationships between the main characters of the analysis: Fremen, planet, colonizers. Although the colonizers are not one society, they are included here as one main character in relation to the other main characters.
- mezzo level – the internal relationships of each of the main characters. Here, due to the plot of the film, we see the internal relations of the colonizers (between the families, between current and former planetary administrator, families and the Emperor). In this part of the story, which has been adapted into a movie, we hardly see the relationship between the Fremen. At this scale, one could find relationships between different parts of the planet, but such an analysis already goes beyond the architectural patterns that are the subject of this article's research.
- micro level – these are the internal relations and histories of the families.

4. PATTERNS USED

The purpose of this article is not to list all the patterns named by Alexander – after all, each pattern could be considered to be presented as present or absent as a procedure to present negative characteristics and highlight a social problem – but to review those patterns that are indisputably used to build a plot, tell a story or provide information that allows the viewer to learn more about the created world. Given the complexity of the design choices in the film, certain patterns are more directly linked to the narrative and emotional impact, while others may subtly shape the atmosphere and cultural backdrop without overtly influencing the plot. The patterns chosen for analysis are those that contribute most significantly to the unfolding of the story, helping to highlight key themes and relationships. Thus, this review of patterns is not just a technical analysis of architectural elements, but also an exploration of how these elements are employed to enhance the viewer's understanding of the world and the characters within it.

The selection of patterns is burdened by a subjective view of the patterns in the book "The Language of Patterns" and the reception of film architecture, also in a subjective way. As with any interpretative analysis, the identification of patterns is influenced by the context in which they are observed, the intentions of the filmmakers, and the viewer's personal experiences and expectations.

In parentheses are given the pattern numbers according to the numbering in the book.

4.1. Towns

- Subculture Boundary (13) – the pattern implies the requirement that different subcultures be separated by some physical barrier so that they can maintain their identities. In the film, the city of Arrakeen is built on rocks, even surrounded by them. Also built in accordance with the pattern and shown in the film are the meeting places of Fremen and colonizers on the seam that runs between the two subcultures.
- Four-story limit (21) – Alexander, for reasons of psychological well-being and the possibility of establishing unforced social relations, proposes to set the height limit for buildings at 4 stories. The city built around the residences basically follows this pattern. The entire city appears to be standardized in terms of height. The exceptions are irregularly placed taller buildings and the governor's residence itself (which follows the pattern of High Places (62), which will be discussed later in the article). The pattern of a four-story limit is used to reinforce the character and importance of the function of the governor's residence.
- Sacred Places (24) – the pattern emphasizes the importance of and the need to protect places that make us feel a stronger connection to the area, convey values related to the past and embody relationships with the land. The governor's palace has a sacred garden with trees. It is a sacred place for the Fremen. Pilgrims come there. And the trees themselves are described by the gardener as an "old dream." The scene where one of the characters conveying emotion is this garden, which is particularly poignant, is the moment when the palace and city are attacked by the Emperor's forces – the burning palms of this "sacred place" for the Fremen, which was cared for by them, and respected and supported by all the colonizers up to that point, are then shown. The brutality, disrespect for life, force, contempt for others, domination, going for the goal at all costs, hatred, disrespect for culture on the part of the Harkonnen and the Emperor are then shown. [Durrani 2023]
- Men and women (27) – every building and space should be created and adapted by men and women. This pattern is strongly evident in the relationship between the families and the Emperor and the Bene Gesserit female order [Risvandi and Fikri 2024] – from the outside it looks like a very masculine world and relationships, in fact it turns out that women play a large role in it. The same is true of the architecture – from the outside it is masculine, but in the interiors and details the feminine elements are evident (wall decorations, bas-reliefs).
- High Places (62) – by using this pattern together with the Limit 4 stories pattern (21), the prevailing political system of the distribution of power on the planet is emphasized (the Emperor rules the entire universe, one family is the executor of power on the planet and dominates the indigenous population). Alexander suggests that tall buildings, point-wise, should be designed as an average of 1 per 7,000 population. There are many towers (visible from above) scattered throughout the city, which can be assumed to maintain the 4-story limit. They are not very dominant, but tall enough to stand out from their surroundings and can be

observation points. The dominant building in the scale of the whole city is the governor's palace. It towers over the entire development. Also, its area and volume even overwhelm the surrounding city.

However, even the palace is not the tallest place in the area. Rocks dominate the entire man-made environment, showing the power of nature on the planet. Sending the message that humans have not tamed nature, that it is not given to them, although they extract raw materials from it.

- Ponds and streams (64) – Dune is a desert planet. Water is locked deep beneath the surface, and every drop of it is very precious. The Fremen have created special costumes that collect and filter sweat so that no drop of water goes to waste. The Alexander pattern shows the value of water in cities. He encourages the protection of natural bodies of water, collecting rainwater, bringing water from underground to the surface, creating fountains and places to contemplate water. The city or palace itself lacks surface water, with no ponds, streams or fountains at which to gather. However, water is one of the most important elements of the plot. The Fremen's dream is to free the water and make the planet green. In this context, it is even brutal and wasteful to build an entire city and palace out of concrete, which binds the water within itself. This can be perceived as an attempt to show the colonizers' domination of the planet and the local population.
- Sacred ground (66) – what is considered sacred should remain difficult to reach, requiring discovery, waiting and levels of access. Every community needs places where, as we pass through successive areas containing ourselves, we arrive at the sacred center, the inner sanctuary. Ch. Alexander even states that "when a community has such places, a sense of holiness will gradually awaken among the people who share this experience." The inner sanctuary was shared between the colonizers and the Fremen. The trees in the inner sanctuary described earlier, the limited accessibility of the place and the need to go through layers of access (desert → wall → city → residence → place designated for pilgrims → inner courtyard with garden), the building inaccessibility of the place combined with the verbal prophecy builds in the Fremen a belief that one of the colonizers (Paul Atreides) is the messiah they are waiting for.

4.2. Buildings

- Connected buildings (108) – according to Alexander, isolated buildings are a sign of a broken society. Buildings connected to each other, touching each other, with no unnecessary spaces between them, force people to interact with each other and adapt to the "vast and more impenetrable" reality of the outside world. In the film world of Dune, we have a city that is very compact. One reason for this may be the city's limited space by the rocks that provide security. But it is also underscored by the need to unite the colonizer community with each other, to create strong bonds in opposition to threats lurking from outside.

- Tree Places (171) – Alexander points out the need to nurture trees planted by humans until they create social spaces and can survive without human care. He reveals how psychologically important a role trees play in human life (as a symbol of personality, fullness and development, drawings of trees are used during projection tests). He argues that trees planted in cities will not satisfy the longing for trees when the places they create are not respected. This pattern in the film adaptation is used to show the Fremen's dream, to build and nurture hope (as the trees are tenderly watered). The trees are planted in rows in the square, at distances large enough that their crowns do not meet. They are arranged evenly, in straight lines and identical spacing. They don't have a chance to create the social spaces Alexander writes about, even though they try (they are on two sides of the square, forming its walls). The emperor, with the hands of the ruling family on the planet, gives illusory hope of fulfilling the dream of a green planet, when in fact it is a place showing domination – the existence of the trees depends on the colonizer, they are inside the city, on the palace grounds, they exist by grace and can be part of the political game.
- A Gobelin of Light and Darkness (135) – this pattern tells how important the role of light and shadow is in an interior. By using lighting appropriately, we can create a striking setting for events. People instinctively turn and move toward the light. In the rooms in the governor's palace, even though they don't have a lot of openings, this pattern is very evident. The interiors where the movie scenes take place are even made of light and darkness. Spaces illuminated through gaps in the walls or ceiling draw the viewer's eye and add drama to dialogues or events.
- Secret place (204) – there should be a place in the house that is hidden, whose existence no stranger will guess. This allows you to create a secret and share it in an intimate way only with insiders. We see one such place in the governor's palace when, after a failed attempt to assassinate Paul Atreides, we discover a Harkonnen soldier walled up in the wall (6 weeks earlier). Of course, there is no sharing of intimacy between the Atreides and the Harkonnens. Rather, about hostility, hatred and the demolition of a sense of security. About marking the lack of a good relationship between the families.

4.3. Constructions

- Space next to poles (226) – poles play an important social role. Even a single pole accentuates a certain point, divides a space and at the same time defines a new space around it – provided it is thick enough. In the film, in the Imperial Ecology Research Station, in the middle of one of the rooms is a large pole with a hole above it. There was research being done here on releasing water hidden in the planet until a valuable raw material was discovered, a spice that would disappear along with the appearance of water and plants. This pillar is definitely larger than Alexander's good pillars describe, on a human scale it is even too large to produce social space. We see this room when the shift judge tries to help Paul

after the Harkonnen attack on the city: a scene is shown when several Fremen sit under the pillar preparing coffee for them and the Atreides (which can be seen as a symbol of friendship). Even when the Emperor's soldiers silently descend, intending to kill everyone in the station, the Fremen manage to hide under the sands and attack them by surprise. Although in the end most of the people in the station are killed (except for the 2 main characters and the shift judge), the pillar allows the viewer's attention to be focused in the right place and has built a sense of stability and safety – a rest after escaping from the attacked palace. Using contrast (safety, hiding place – attack, death), a sense of brutality on the part of the Emperor towards the Atreides family was also built in the viewer.

- Ornament (249) – Alexander states that ornaments are as important in a building as doors and windows. Ornaments are not just for decoration (although everyone tends to decorate), but make the world or space more whole. Ornaments especially work at the junction – between two elements binding them together as if seams, where there are two edges (of materials, walls, worlds, spaces, cultures...). The austere and brutalist architecture of the colonizers on Dune seems to have no need for ornaments. After all, it is "only" useful, it is supposed to provide shelter and continuity in the extraction of a valuable resource. However, even here ornaments appear, stitching the spaces together. One boundary that is visible and is decorated with ornament is the partition between the tree plaza (the plaza, which is a sacred place, sacred ground and tree place) and the place where the Fremen pilgrims come. The metal grating is carved, which contrasts with the simplicity and lack of ornamentation in the plaza and building walls. There is a clear boundary between two cultures and two spaces. It seems that the creators of the concept may have wanted to stitch the boundary between the square and the hope provided by the trees, and the place for pilgrims and their "unfulfilled dream." One can also see an attempt to bring the colonizers and the local population together – for which the willingness of both sides is needed (the Harkonnen family did not show this willingness, unlike the Atreides family). The second ornament is the reliefs in the palace. They are seen in the company of Paul Atreides. So is the previously mentioned metal partition. Paul, in a way, becomes a sort of guide to the palace for the viewer. One of these bas-reliefs depicts the Shei-Hulud, the brood of the desert – a threat to the colonizers, a symbol of the planet's power, a producer of extracted raw material and a sacred creature to the Fremen. The second bas-relief is in Paul's bedroom and depicts fish. It is interesting and significant that the director cared that these ornaments were made in reality.
- Objects from your life (253) – the things that surround us play an important role in the continuous process of self-transformation, if they are personal, chosen instinctively, have meaning for us and tell our personal story.
  In the film, amid the non-personal architecture and interiors of the palace (after all, another family had previously run the planet), there was no room for the motif of a personal object. The ring that Paul found in the packet of life-saving

items during the escape becomes his personal only after leaving the non-personal architecture. The ring previously belonged to his father and is a symbol of the transfer of power and the duration of the dynasty.

4. SUMMARY, CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

The diagram in Fig.1 maps the frequency and distribution of architectural patterns, as defined by Christopher Alexander, onto the relational structures depicted in Dune (Villeneuve, 2021). These relationships – visualised as connections between key narrative agents (the Fremen, the colonisers, and the planet) – reveal a dense presence of patterns across Alexander's three main scales: town, building, and construction. Furthermore, these patterns are evident across all relational levels in the film's diegesis: macro (intergroup), mezzo (intragroup), and micro (intrafamilial). The application of Alexander's system in this analysis allows for a new interpretive frame through which to consider the architectural dimension of cinematic world-building and its role in visual storytelling.

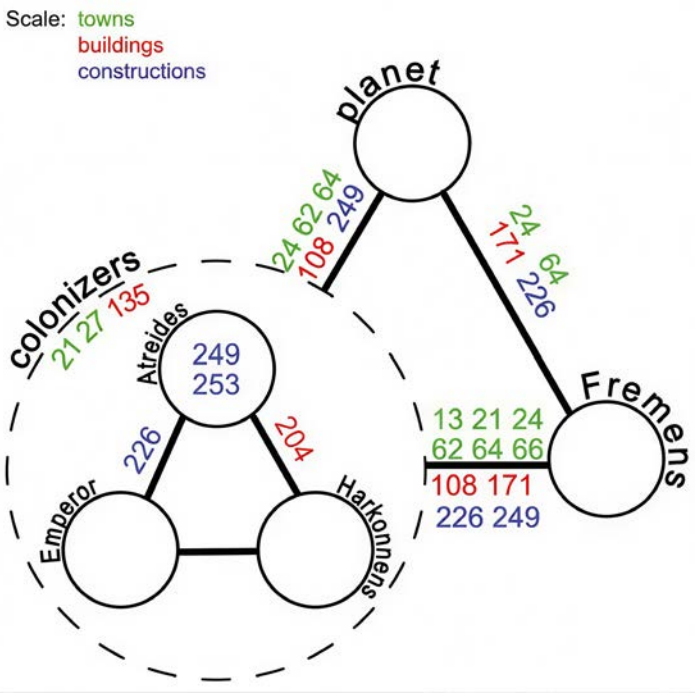

Fig. 1. Summary of characteristic features describing the architecture on Arrakeen [own study]

On the macro level – representing the relationships between the major group entities – the architecture reflects and reinforces the dynamics between the Fremen, the colonisers, and the planet Arrakis itself. The highest concentration of patterns (10) is found in the relationship between the Fremen and the colonisers, followed by five in the coloniser–planet relationship, and four in the Fremen–planet connection. These figures correspond to the narrative focus of Dune, which explores the consequences of imperial power shifts, resource extraction, and the formation of new alliances. Notably, the visual language of architecture often anticipates or echoes the tensions between these groups: expansive monumental forms signal dominance, while subterranean, concealed structures suggest resistance and autonomy. This suggests that architectural space in Dune is not merely decorative but ideologically charged. This use of architectural mise-en-scène aligns with theoretical perspectives that treat space as an expressive element of narrative cinema [Bordwell and Thompson 2009]; [Branigan 2013].

At the mezzo level, architectural patterns illuminate the internal organization of the colonizing forces themselves. Here, patterns signal enduring power structures that transcend individual characters or families. For instance, pattern 21—"four-storey limit"—is visible in the consistent height of administrative buildings, which symbolically concentrate power and facilitate surveillance, regardless of whether the Harkonnens or Atreides occupy the city. Pattern 204 – "degrees of publicness"—captures the spatial separation between noble factions and the general populace, also serving to externalize political hostilities between Atreides and Harkonnens. These internal architectural codes stabilize the image of colonial governance, even as the governing family changes, suggesting that architectural form outlasts and regulates political transition.

On the micro level, the patterns function primarily at the scale of construction, encoding family histories and inherited identities. One example is pattern 253—"things from your life"—represented by Paul Atreides's signet ring, which symbolizes dynastic continuity and political legitimacy. Although such patterns are relatively fewer, their presence suggests that even small-scale architectural or artefactual details may participate in the narrative economy, especially when used to signal themes such as inheritance, legacy, and destiny.

Taken together, these findings support the argument that the architectural patterns employed in Dune are not incidental but narratively functional. The deliberate deployment of Alexander's spatial principles allows the architecture to act as a mediating agent between viewer and narrative, encoding symbolic relationships that may not be explicitly stated in dialogue or plot. The built environment thereby emerges as a semiotic system—what might be termed a cinematic pattern language—through which relational, political, and emotional tensions are visually structured and communicated. In this sense, Dune supports the hypothesis that

architecture, when designed and framed with narrative intentionality, can function as a storytelling agent.

This interpretation extends beyond the descriptive into the theoretical. When architecture assumes this semiotic role, it challenges the conventional status of setting as inert backdrop. Instead, it becomes a kind of "spatial actor" within the narrative, endowed with agency insofar as it can influence behaviour, reflect psychological states, and reinforce ideological orders. This agentic function aligns with emerging theoretical perspectives in film studies, which explore the intersection of spatial aesthetics, cinematic narrative, and material culture. If Alexander's patterns serve as archetypal spatial forms—recognisable even when not consciously perceived—they may constitute a universal visual lexicon through which viewers intuitively decode meaning.

However, this case study remains limited in scope. It focuses on a single film, albeit one of unusual architectural density, and does not yet establish whether such use of pattern language is systematic across science fiction cinema. Future research could address this limitation by examining other architectural environments within Dune, such as the Fremen sieges, the water-centric architecture of Caladan, or the oppressive structures of Giedi Prime. Each of these spatial settings is governed by different design logics, potentially grounded in their respective cultures' ideologies, values, and survival strategies. Comparative analysis of these sites may yield further insight into how spatial form reflects social structure in speculative worlds.

A second avenue of inquiry lies in auteurist comparison. Denis Villeneuve's Blade Runner 2049 (2017), for instance, similarly engages with architecture as a carrier of memory, control, and ecological anxiety. Identifying recurrent spatial motifs in Villeneuve's work may help determine whether his use of Alexander's principles constitutes a directorial signature or a thematic concern particular to Dune. Alternatively, analysis could be extended across science fiction or fantasy genres more broadly to test whether architectural patterning constitutes a genre-specific visual grammar. This would involve examining whether Alexander's language of patterns is adaptable to varied world-building traditions and visual conventions.

In conclusion, this study suggests that Christopher Alexander's pattern language, when applied to the analysis of speculative cinema, offers a productive framework for understanding how architecture operates narratively. Far from being decorative or backgrounded, built environments in Dune act as dynamic narrative components that spatialise the film's core themes of power, identity, and transformation. Whether such patterns represent a universal grammar of cinematic space or a distinctive feature of Villeneuve's style remains an open question—but one with promising implications for future interdisciplinary research.

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„JĘZYK WZORCÓW" W KINIE: SEMIOTYKA PRZESTRZENI W FILMIE „DIUNA" VILLENEUVE'A

Streszczenie

Artykuł bada możliwość zastosowania języka wzorów Christophera Alexandra do analizy architektury filmowej, wykorzystując jako studium przypadku film „Diuna" (2021) w reżyserii Denisa Villeneuve'a. Badanie analizuje, czy wzory architektoniczne mogą funkcjonować jako język wizualny, który przekazuje relacje, hierarchie i dynamikę władzy w ramach filmowej narracji. Poprzez diagramatyczne odwzorowanie wzorów Alexandra w trzech skalach – miasta, budynku i konstrukcji – badanie identyfikuje ich powtarzalność w strukturze narracyjnej filmu „Diuna". Wyniki sugerują, że architektura w filmie pełni nie tylko funkcję dekoracyjną, ale także semiotyczną i narracyjną, kształtując postrzeganie przestrzeni, emocji i ideologii przez widza. Łącząc projektowanie przestrzenne z relacjami międzyludzkimi i politycznymi, środowisko „zbudowane" filmu staje się systemem ekspresyjnym, który wspiera narrację. Badanie stwierdza, że ramy teoretyczne Aleksandra stanowią cenne narzędzie analityczne do interpretacji budowania świata filmowego i sugeruje kierunki dalszych badań nad innymi filmami science fiction w celu oceny uniwersalności tego podejścia. Dalsze badania w tym zakresie mogą obejmować kolejne przestrzenie architektoniczne ukazane w tym filmie, pozostałe filmy tych twórców i inne filmy, by potwierdzić nieprzypadkowość.

Słowa kluczowe: kinematografia, architektura filmowa, Język wzorców, psychologia architektury