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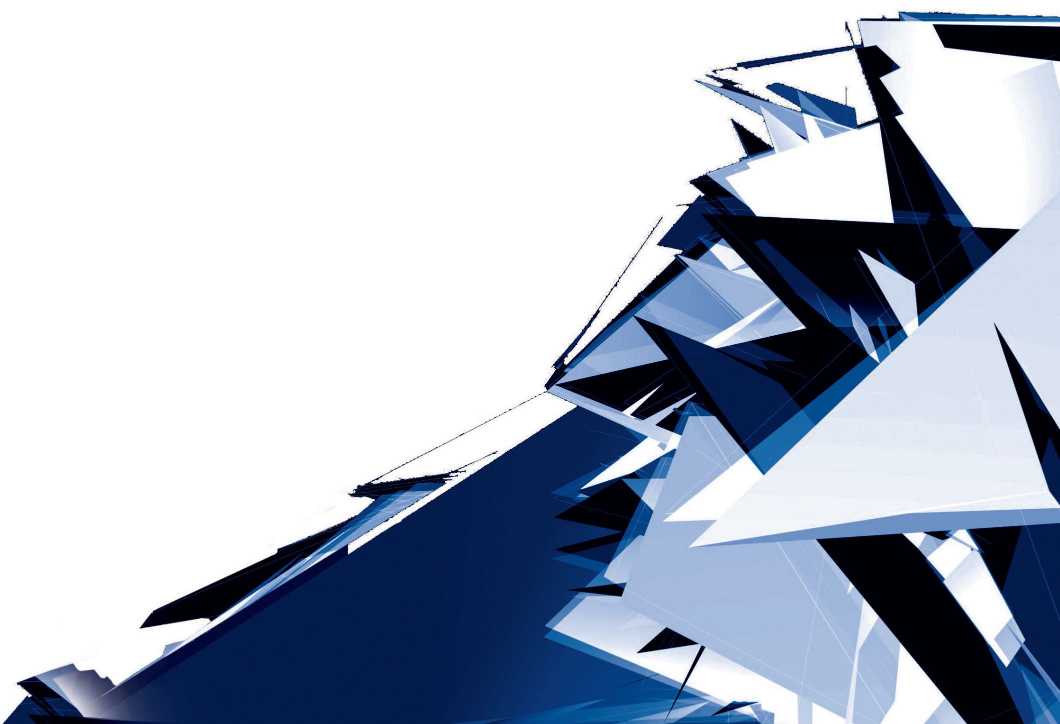

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The role of the Vistula river in the spatial development of riverine residential districts in Cracow

Rola Wisły w rozwoju przestrzennym nadrzecznych dzielnic mieszkaniowych w Krakowie

Abstract

An important factor in the location of the first human settlements was access to a river. Connected with industrialization, the progressive process of turning the city away from rivers caused the degradation of watercourses and their surroundings. Degraded rivers have become a shameful problem and a barrier to intensively developing cities. In the 21st century, the advantages of well-developed boulevards were recognized. This article analyzes the role of the river in the urban spatial development and public spaces related to the river. In addition, opportunities for the improvement of riverside urban spaces are presented on the example of the area of Stare Dębniki and Salwator in Cracow. Detailed variants were developed as part of the *Przepis na miasto* workshops.

Keywords: city, river, boulevard, spatial development, public space

Streszczenie

Ważnym czynnikiem lokalizacji pierwszych osad ludzkich był dostęp do rzeki. Związany z industrializacją, postępujący proces odwracania się miasta od rzek spowodował degradację cieków i ich otoczenia. Zdegradowane rzeki stały się wstydliwym problemem i barierą dla intensywnie rozwijających się miast. W XXI wieku zaczęto dostrzegać zalety dobrze zagospodarowanych bulwarów. W niniejszym artykule dokonano analizy roli rzeki w rozwoju przestrzennym miast i przestrzeni publicznych związanych z rzeką. Ponadto, przedstawiono możliwości poprawy nadrzecznych przestrzeni miejskich na przykładzie obszaru Starych Dębnik i Salwatora w Krakowie. Szczegółowe warianty opracowane zostały w ramach warsztatów *Przepis na miasto*.

Słowa kluczowe: miasto, rzeka, bulwar, planowanie przestrzenne, przestrzeń publiczna

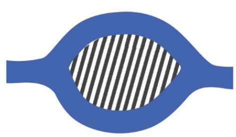
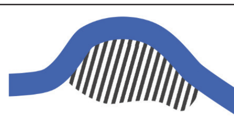
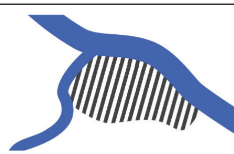
1. The role of the river in the development of a settlement

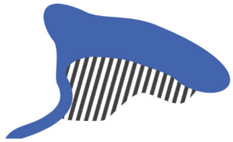
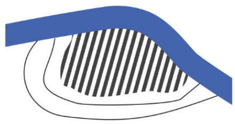
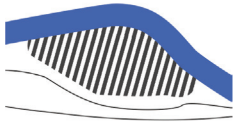
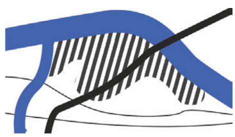
The rivers have long been influenced by settlements. The development of cities took place on the banks of rivers, and metropolises formed in the basins. The reason for this was the fact that the river was an indispensable factor for human and animal life. Rivers were also an important element of the defense system of cities, they supported communication and trade. Rivers also played an important role in removing urban pollution. The vicinity of the river was a significant influence on the economic development of the cities near it [8].

From the point of view of history, the link between the location of cities and their dependencies on the river is undeniable. The river in the vicinity of the city brought with it dangers like floods. Nevertheless, the river played a very important role in the development of many cities. The analysis of the oldest medieval cities allows to conclude that differences between them in the manner of development result from the chosen location. The analysis of maps of medieval cities allows to distinguish nine types of city locations in connection with the river. The characteristics of the location of historical settlement complexes on the river is contained in Table 1 [8].

Analyzing the spatial development of riverside cities, it can be noticed that the natural environment strongly influenced their shape and spatial extent. Initially, cities were built on one bank of the river. The reason for this were defense issues. For some cities, the river did not constitute a barrier to spatial development; for others, it was an obstacle [8]. In most cases, as time passed, areas designated for the city ceased to be sufficient. Economic growth, demographic growth and flood hazards contributed to moving beyond the scope of old urban centers. The cities gradually began to consist of many settlement units, in which the river affected the plan and character of the development. The first suburbs were absorbed on the same side of the river as the city. The second in the order of the cities were included undeveloped suburban areas. Connected areas in one settlement complex were often characterized by a separate character of development or compactness of buildings. This created an impression of urban chaos and incoherence [8].

Table 1. Characteristics of the location of historical settlement complexes on the river

Location	Graphic diagram	Example
On the island formed by the arms of the river		Wroclaw on the Oder Poznan on the Warta Paris on the Seine
On an elongated promontory, surrounded on three sides by a river bed		Besancon on the Doubs
Between the river and its tributary		Lyon on the Saona and Rhone

Between the lake and the river's backwaters		Geneva on the Rhone
At the mouth of the river to large water bodies		Szczecin on the Oder and next to Szczecin Lagoon
On the hill above the river or on the high terraces of its valley		Warsaw on the Vistula Cracow on the Vistula Prague on the Vltava
Place where the river crosses with an important land trade route		Torun on the Vistula Jaroslaw on the San Przemysl on the San
Location in the valley, mostly in the overflow terrace		Gdansk on the Motlawa
Mixed systems		Cologne on the Rhone Bilbao on the Nervion

(Source: [8])

2. The importance of the Vistula in shaping Cracow

In the case of Poland, not all rivers were a factor in the development of urban centers. They influenced the local settlement system to varying degrees [3]. Vistula had a great significance in shaping the cities in Poland. Cracow was at its bank. The city was located on the Wawel Hill at the foot of the Vistula River and on the terraces at the mouth of the Rudawa and Prądnik. It was located at the intersection of roads. It was one urban organism. In the mid-nineteenth century, the city was surrounded by a ring of fortifications. Cracow developed within the limits set by defensive walls, but its dynamic growth and the development of its urban functions influenced the revival of the settlements located in its immediate vicinity: Kazimierz and Kleparz [5]. Rudawa was of great importance to Cracow. The original channel of the Rudawa ran along today's 3rd May Avenue, creating numerous backwaters in the area of Blonia, joining at the confluence of today's streets: Wenecja and Garncarska with

Mlynowka Krolewska, to reach the Vistula along today's Retoryka street [17]. Very soon, the residents noticed that Rudawa could be used economically. Already in the thirteenth century, Mlynowka Krolewska was created, an artificial riverbed directing the river to the Dominican monastery within the city. It was also part of the city's fortification, providing security. It is worth mentioning that in the moat and in the upper reaches of Młynówka, i.e. above the water intake, fish were raised. Their presence was not irrelevant there. Firstly, it allowed to follow the purity of the watercourses (the fish die if the water was too polluted) [16]. Second, it was a reservoir of food in the event of a siege of the city. Importantly, the water from the Rudawa was widely used by residents for everyday activities. Despite the proximity of such a large river as the Vistula, Rudawa was more important at that time. All because of the Vistula flowing too low. Rudawa had a much larger drop, and hence, more energy that could be used [16]. It was additionally intensified by damming the water with a weir in Mydlniki. The Vistula was a huge pool, and it could be not tamed it as much as the smaller Rudawa.

Due to the location of Cracow, floods were a big problem for its residents. The 19th and 20th centuries were the most destructive. Zygmunt August already issued a ban on construction along the Młynówka river to protect the people from the tragic consequences of great water. Only industrial plants could be located there. Successive kings upheld these bans, but they were systematically broken by the inhabitants. The decision to close the Młynówka river bed was made after the flood in 1903, during which its backwaters caused the most damage in the center of Cracow. Another of the activities leading to the remoteness of the watercourses from the city after the tragic flood in 1903 was redirecting the Rudawa in 1907–1912 to its current embanked canal that flows to the Vistula on the Rodlo Boulevard near the Norbertine monastery [5, 16]. It was established long before this, because in the seventeenth century, it was supplying water to the monastery farms and breeding ponds. The previous Rudawa channel has been buried in this section. In the place of the closed trough, a low-alley alley was created, separating two street routes [12]. Thanks to the drainage and protection works carried out on the Vistula and Rudawa, new areas, which were located in the vicinity of the central part of the city, were obtained. These areas became a release from the flood threat and could be used for investment and construction purposes. For years, Cracow has moved away from the river. The only areas closely related to the river are the Vistula boulevards. The spatial development of Cracow has been unrelated to the Vistula for years. The desire to connect the Vistula residential districts with the Vistula became the reason for writing the article.

3. Forms of urban public space connected with the river

In the second half of the 20th century, the process related to the revitalization of riverside areas was initiated in the development of riverside cities. It consists of addressing cities to the river [6]. In recent years, fashion on the quay has taken on a global dimension and changed the way of thinking about water and its neighborhood. Riverside areas are subject to discussions, analyzes and undertakings regarding urban development planning, urban planning and architecture [4]. The riverside areas in the city are areas that accompany the river in its immediate vicinity and depend on its benefits and threats. This concept includes developed fragments of banks that lend space to the river, creating its functional and scenic frame. The outline of riverside areas is marked by the adjacent buildings and mass of greenery, or other compact sets of objects that can be considered a wall of a landscaped interior stretching along the river [2]. At present, the renewal of spatial and functional relations between the city and the river is one of the important problems of riverside cities development [7]. The evolution of city-river relations relies on the cities turning in front of the river by reusing (revitalizing) the riverside areas and shaping new functional and spatial relationships with the river [4]. The revitalization of riverside areas is one of the important development trends observed in many riverside cities and the challenge facing these cities in the 21st century. The revitalization of riverside areas is a response to the process of earlier degradation of these areas. The direct cause of the transformation of riverside areas is also the growing social demand for such individual places. In European port and riverside cities, the importance of riverside areas and recognition of their location attractiveness has been rediscovered. A significant role of the river and the coast in the identification of cities, large cultural values and historical rivers as well as riverside areas have been noticed [6]. Among the model projects of the revitalization of urban riverside areas are: Bilbao, Manchester, Amsterdam or London. The best large-scale urban projects come from Lyon, Hamburg and Berlin [4, 10].

The revitalization of the banks of the Nervion river in Bilbao is undoubtedly the most popular example of returning the river to the city. To stimulate the city, a plan was created to transform the former shipyard's grounds into a cultural and entertainment center. In

Fig. 1. Guggenheim Museum in Bilbao
(source: [18])

addition, it was supported by a number of other activities, such as the renewal of housing in the city center and the expansion of the communication node. The quay was developed with a diversified function: residential, service and cultural (Guggenheim Museum, Figure 1) [9]. This contemporary object caused that all space in the immediate vicinity of the river came alive. The museum caused that the Nervion river boulevard became a new quality space, attracting residents due to new, attractive places of residence and work, but also became a tourist attraction. This 'revival' of the city was referred to as the 'Bilbao effect' [1].

Another example of good practices in dealing with riverfronts is Hamburg. The river has a different role in Hamburg than in Cracow because it is a port city, despite Hamburg being one of the best examples in Europe on how to deal with a river. The idea of a new inner-city district was conceived soon after the fall of the Wall and the Iron Curtain. Before the publication of the blueprint for HafenCity, the Masterplan, in 2000, important fundamentals had already been put in place in the 1990s. HafenCity Hamburg is a project of urban regeneration where the 'Grosser Grasbrook' area of the former Hamburg free port is being revitalized with new hotels, shops, office buildings, and residential areas. The project is considered the largest urban redevelopment project in Europe by landmass (approximately 2.2 square kilometers) [15]. An example of the restoration of water to the city as the main element of spatial composition is undoubtedly the Santiago Calatrava City of Arts and Sciences located in the drained bed of the Turia River in Valencia. The area of almost 360 square meters has been designed with futuristic buildings, which house an oceanarium, a science museum and an opera, surrounded by swimming pools and exotic gardens [9].

4. Riverine area development in the Cracow Urban Programs

The future of Polish cities depends on the program assumptions of the city authorities and their implementation. Cracow residents have been observing the creation of numerous new housing complexes, public buildings and service facilities for several years. At the same time, their awareness of rational land use and sustainable development has increased. Residents have higher expectations in work and residential places, reliable transport system, but also friendly public spaces and access to decorated urban greenery. Cracow, like other large cities in Europe and around the world, faces significant development challenges.

Cracow Development Strategy "I want to live here. Cracow 2030."[1] is a document defining the basic directions of socio-economic development over a longer period of time. It is one of the most important documents from the Cracow Urban Programs, which defines the following strategic purposes [13]:

1. Cracow as an open and harmonious metropolis of international significance in the areas of: innovation, science, economy and culture.
2. Cracow as a city developing a knowledge-based economy.
3. Cracow as a modern metropolis that is creative as well as using cultural potential.
4. Cracow as a city that is friendly to life.

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1 Strategia Rozwoju Krakowa *Tu chcę żyć. Kraków 2030* – transl. note.

5. Cracow with a strong local self-government community of Cracow residents.
6. Cracow as a modern managed metropolis.

The implementation of the fourth purpose is focused on the creation of new public spaces, improvement of environmental quality standards and urban space revitalization. This document [13] contains a number of strategic projects, including some directly related to the Vistula River:

- creation of river parks (rivers: Vistula, Drwinka, Dłubnia, Wilga, Sudół Dominikański, Białucha),
- construction of the Kazimierz – Ludwinów shared cyclist-pedestrian footbridge,
- creation of Zabłocie Park – "Wisła Station",
- revitalization of areas near the Kotlarski Bridge – Podolski Boulevard,
- construction of "Marina Krakowska".

Study of the Conditions and Directions of the Spatial Management of a Cracow Commune[2] [14] is, apart from the Cracow Development Strategy, the most important planning document of the commune. The study is prepared in order to determine the spatial policy of the commune, including local spatial development regulations. The study regulations are binding for the prepared local spatial development plans, thanks to which the vision included in the study affects local regulations and shapes the commune development. The study implements one of the basic local government responsibilities, which is creating the spatial order which is the basis for the Cracow development.

Study of the Conditions and Directions of the Spatial Management of a Cracow Commune [14] defines the directions of changes in the development of areas located in the urban zone:

- intensification of investing with preservation and protection of existing public greenery complexes, city squares and green zones,
- modernization of degraded areas with replacement or rehabilitation of buildings and recomposition of urban layouts,
- ordering extensively used space, threatened by urban chaos through land reparcelling and consolidation,
- use of preserved open areas, especially those located along rivers and streams, for shaping publicly available city parks,
- preservation of existing structures with high cultural values by consolidating historically shaped urban layouts and maintaining the architectural character of development proper to individual districts.

The main elements forming the spatial structure of the city are public open spaces. Open areas are primarily those that are or will play a role not only in the natural environment, but first and foremost in the public. Over the last few years green areas have been significant in the Cracow spatial policy. In the Study of the Conditions and Directions of the Spatial Management of a Cracow Commune defines main directions of green areas development:

- forming the municipal public greenery system based on existing natural resources,
- the arrangement of green areas as public spaces with high aesthetic, natural, functional and landscape values,

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2 Studium uwarunkowań i kierunków zagospodarowania przestrzennego Miasta Krakowa – transl. note.

- improvement of legal protection of areas with the highest natural and landscape values,
- forming the spatial connectivity of pedestrian and bicycle routes of public green spaces and open areas, with particular emphasis on riverside greenery within river parks.

On 1 July 2015, the new administrative unit (the City Green Board[3]) was established in Cracow. The unit was created with the aim of taking care of almost all green areas in Cracow: parks, forests, green areas and squares, greenery estates, road lanes and Vistula Boulevards. In 2017, a comprehensive document was enacted, taking into account only greenery. 'Directions for the development and management of green areas in Cracow for 2017-2030[4]' [11] defines local development policy for green areas. As in the Study of the Conditions and Directions of the Spatial Management of a Cracow Commune, in this document, the Vistula River was distinguished and the Vistula River Park was planned. It is a collection of projects whose common denominator is the reconstruction or revitalization of coastal areas of the Vistula River. These include projects of key importance for the development of metropolitan functions of Cracow such as: Congress Center, Music Center, Zabłocie Boulevards (public spaces linking the Cracow-Zabłocie railway station with the new Zabłocie museums and housing and service complexes built under revitalization of post-industrial areas) - connected by attractive pedestrian and bicycle routes and other public spaces (squares, view terraces, mini-park sequences, etc.). Significant components of the Vistula River Park project will be actions leading to the revitalization of Stare Podgórze and the continuation of the revitalization of Kazimierz. This collection of projects will also include projects to revitalize the space of squares, including the square in front of Galeria Kazimierz (from the Vistula boulevards) and to create an attractive park space integrating the planned Music Center with boulevards on the Vistula.

5. City facing the river – *Przepis na miasto w*orkshop

In May 2017, a team from the Faculty of Civil Engineering of the Cracow University of Technology[5] organized the Przepis na miasto[6] multidisciplinary workshop. A group of students from the Cracow University of Technology, Cracow University of Economics, Wrocław University of Science and Technology, University of Economics in Katowice, Adam Mickiewicz University in Poznań and European Students of Industrial Engineering and Management participated in the workshop. The end products of the workshop were six charts and mockups of the Stare Dębniki and Salwator in Cracow particular area parts. The fact that the work had a multidisciplinary character was crucial – the students represented branches of engineering associated with transport, spatial management as well as urban and

[3] Zarząd Zieleni Miejskiej – transl. note.

[4] Kierunki Rozwoju i Zarządzania Terenami Zieleni w Krakowie na lata 2017–2030 – transl. note.

[5] WIL PK – Polish abbreviation, transl. note.

[6] The workshop took place between 18–20.05.2017. Krystian Banet and Ewelina Stypułkowska were organising committee chairmen. The workshop was organized by KNSK Student Scientific Association of Transporartion Systems (Koło Naukowe Systemów Komunikacyjnych – transl. note).

architectural design across two levels of higher education (Bachelor, Master). Students' work was supported by a panel of experts: Andrzej Szarata, Tomasz Kulpa, Marek Bauer, Mariusz Dudek, Aleksandra Faron, Katarzyna Nosal, Kinga Racoń-Leja, Agnieszka Szumilas, Ada Wolny. The overall goal of the workshop was an attempt to connect two Vistula river banks, to analyze the urban transport system integration and to propose changes in the selected degraded public spaces.

The common issue of the six projects was to transform the river from a barrier into a connector. The common idea of all of the groups was the construction of the Stare Dębniki – Salwator shared cyclist-pedestrian footbridge. The large distance between the nearest bridges (the Dębnicki and the Zwierzyniecki bridges) was an argument for creating such a connection. The footbridge would increase the accessibility of the Vistula banks, make it easier to move around the city, but would also serve as a vantage point. As it was mentioned in paragraph 3, one of the strategic projects [13] is the construction of the Kazimierz - Ludwinów shared cyclist-pedestrian footbridge. Students pointed to the need for an additional shared cyclist-pedestrian footbridge between Stare Dębniki and Salwator.

The creation of the Vistula river park was also a common issue of the six projects. As it was mentioned in paragraph 3, the creation of the Vistula river park is one of the strategic projects pointed out in the Cracow Development Strategy [13]. Due to it and the Study of the Conditions and Directions of the Spatial Management of a Cracow Commune [14], in which it is said that Cracow should be developed using preserved open areas, especially those located along rivers and streams, for shaping publicly available city park, all groups proposed some ideas for the Vistula boulevard.

The *Discover yourself again*[7] conceptual design assumed the development of the southern Vistula river bank, modeled on Japanese gardens. The garden would be divided into several parts. Each of them would use the experience of one of the four senses: touch, hearing, taste/smell and vision. The goal would be achieved through the implementation of different surfaces, flora or water elements. The garden would refer to the Manggha Museum of Japanese Art and Technology located nearby. It would be an extension of the museum's offer and a presentation of the external elements of Japanese culture. The implementation would not only have a functional, aesthetic and recreational aim, but also an educational one.

The next workshop variant, which adapts Stare Dębniki area to the mobility needs of sight-impaired people, is the *Let's make noise*[8] conceptual design. In this solution, the authors focused on the Rynek Dębnicki square. The concept assumed the revitalization of the public space. In this proposal, the removal of road lanes around the Rynek Dębnicki square was intended to improve pedestrian safety. A reduction in private car traffic has permitted to create friendly public space. The concept assumed the revitalization of the municipal greenery and an introduction of a green pergola on the western Rynek Dębniki square side. In the central part of the Rynek Dębnicki square, the authors designed an interactive board. The main

[7] Authors: Piotr Bielański (CUT), Anna Saletra (CUT), Maciej Górz (CUE), Kinga Kasprzyca (WUST), Alicja Walczak (CUT).

[8] Authors: Jakub Salach (CUT), Małgorzata Stec (CUT), Maciej Pilny (WUT), Justyna Mazur (CUT), Natalia Kobza (ESIEM).

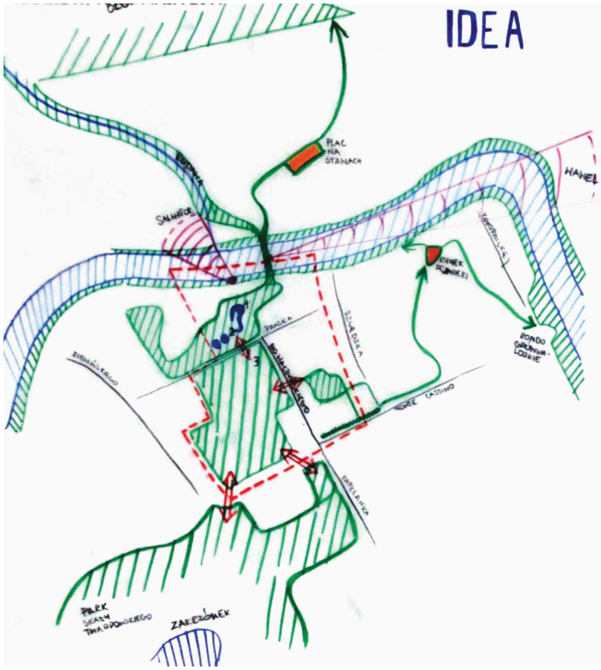

Fig. 2. The *Vistula Garden* – design concept developed as a part of the *Przepis na miasto* workshop (by: Ewa Dyk, Marcelina Smolarczyk, Paweł Ulfik, Aleksandra Fira, Gabriela Frań)

aim of the board is to learn and play using sound experiences, such as clash, crackle, flutter, hiss, jingle, splash, twitter, whistle. The project also involves the installation of demountable wooden platforms on the river bank. The platforms would be an extension of the city to the river. The city would merge with the river. The shoreline would not be a rigid border.

The third idea was the *Vistula Garden*[9], which assumed the use of the proposed footbridge as a link between the green areas located on the opposite banks of the Vistula. The footbridge would connect the green areas of the Dębniki allotments, Dębnicki Park, Vistula boulevards with the extension to the Rudawa boulevards (Figure 2). The project would not only have a functional and recreational purpose, but also an educational one. On the right Vistula riverbank, near Dębnicki Park, the creation of the educational Center of Water was proposed (Figure 3). The Water Center would educate on how important water is, and how you can purify water using natural methods. Similarly to the *Let's make noise*, an assembly of demountable wooden platforms on the bank of the Vistula was established. As it was mentioned in paragraph 3, one of the strategic projects [13] is the construction of "Marina Krakowska". The students proposed to place it on the right Vistula riverbank in the front of Lasocki Palace.

9 Authors: Ewa Dyk (WUST), Marcelina Smolarczyk (CUT), Paweł Ulfik (UEK), Aleksandra Fira (CUT), Gabriela Frań (CUT).

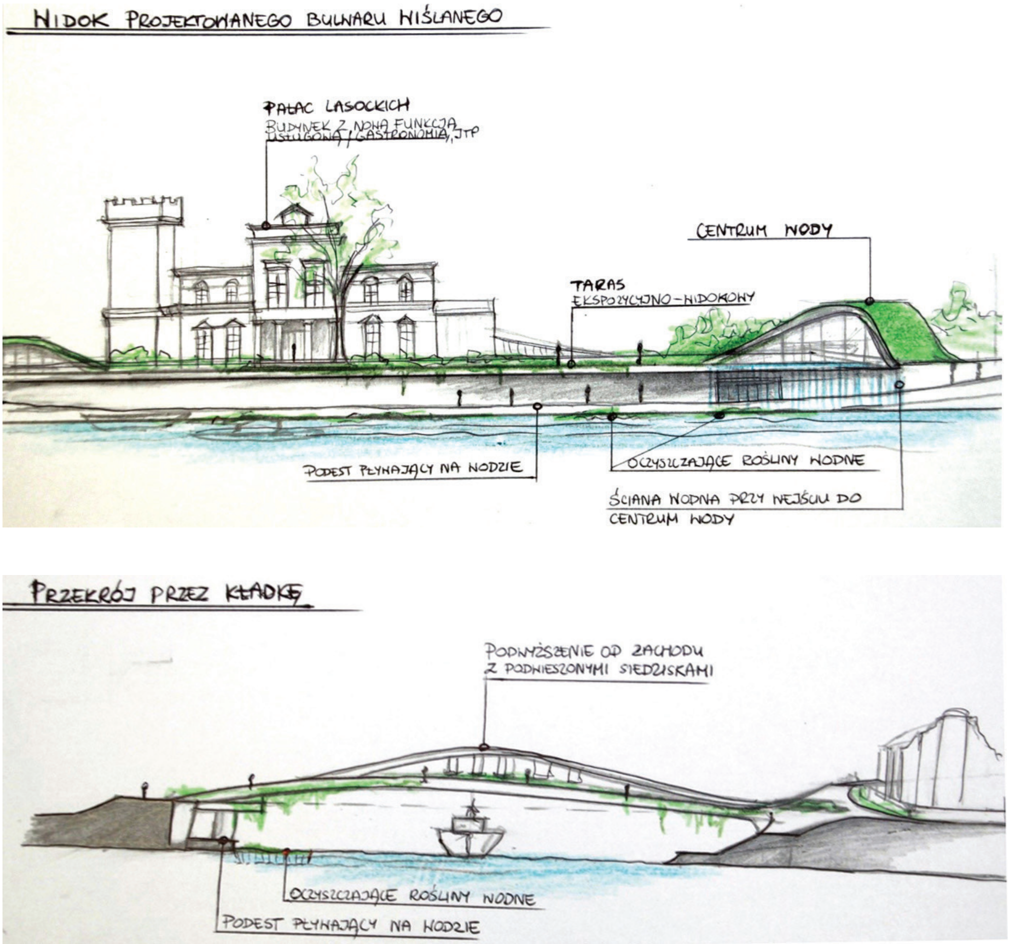

Fig. 3. The *Vistula Garden* – design concept developed as a part of the *Przepis na miasto* workshop (by: Ewa Dyk, Marcelina Smolarczyk, Paweł Ulfik, Aleksandra Fira, Gabriela Frań)

The *Entangled Salwator*[10] (Figure 4) is the last project presented in the article. The concept assumed the use of the Vistula tributary potential - the Rudawa river. The main dominant element of the area is the Norbertine Sisters Priory and the Salwator terminus. Accurate build-up limited the possibilities of introducing new functions. The authors relied on improving the existing state and introducing as much greenery as possible. Hence the concept of greening the terminus by assembling pergolas and climbing plants (Figure 4). On the Rudawa boulevards, it was proposed to create walking and cycling routes in the shape of wavy lines with numerous seats.

[10] Authors: Andrzej Bąk (CUT), Marcin Zaleski (CUT), Paulina Stopka (WUST), Paulina Ziętek (UEK), Angelika Spendel (CUT).

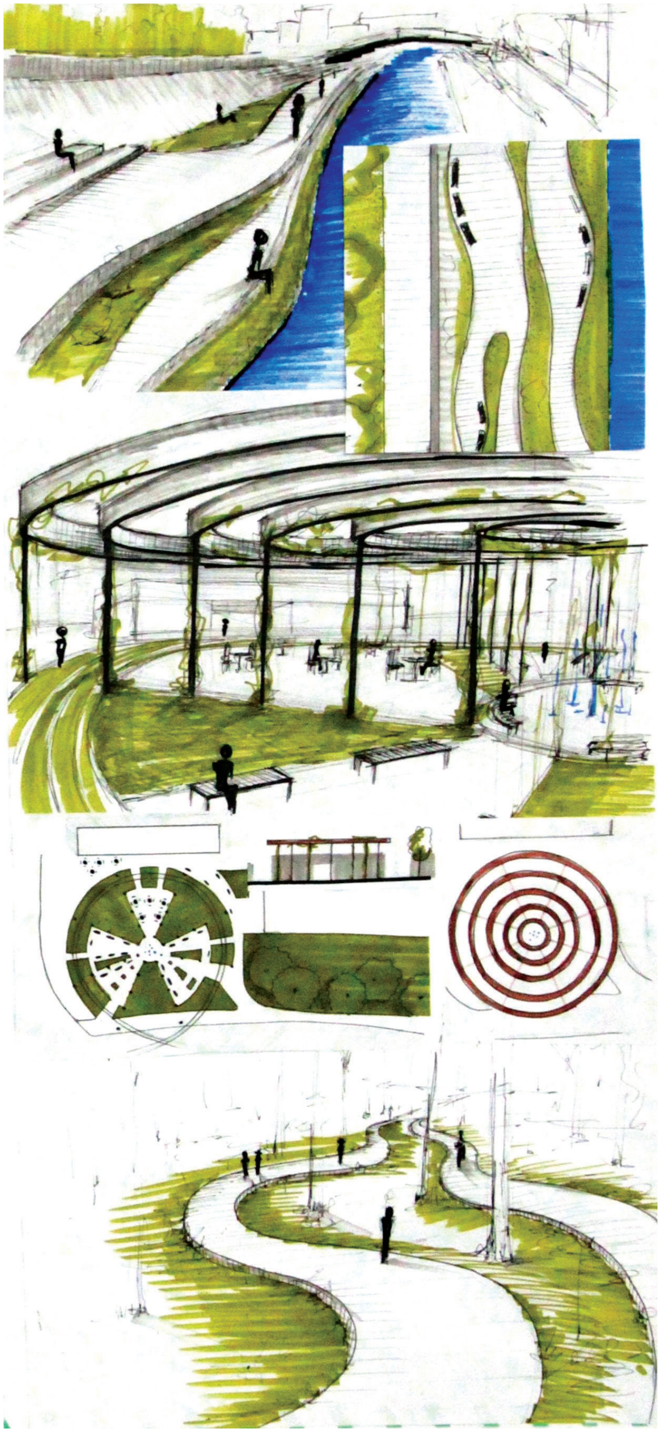

Fig. 4. The *Entangled Salwator* – design concept developed as a part of the *Przepis na miasto* workshop (by: Andrzej Bąk, Marcin Zaleski, Paulina Stopka, Paulina Ziętek, Angelika Spendel)

6. Conclusions

The river is an inseparable element of the urban landscape. Its role is reflected throughout the history of the city's formation and development, from the choice of location, through spatial and functional development, to economic, political and cultural development. The riverside location of the city distinguishes it from other urban areas. Riverside areas emphasize the individual and unique character of riverside cities and become strategically important for the urban development of the city.

The revitalization of riverside areas is a challenge for the 21st century. Many cities are currently in the process of turning towards the river. This process indicates a return to nature and the desire to commune with the nature of people living in cities, as well as to see the resulting benefits. Properly developed boulevards should become a link between the city and the river. Thanks to this, the urban space located above the watercourse gains a new value and becomes an attractive, vibrant part of the metropolis, encouraging to spend free time, rest, as well as gaining attractive places in economic terms.

Cracow sees the advantages of well-developed boulevards. The Cracow Urban Programs include strategies and projects of which aim is to return the city to the river. The authorities began to gradually implement the designated goals. Zabłocie Park – "Wisła Station" opening in May 2018 is the result of Cracow Urban Programs implementation. The city is definitely changing near the Zabłocie district, which is covered by the revitalization program. The city authorities should also remember about the other fragments of the Vistula River, not only those at Zabłocie. During the *Przepis Na Miasto* workshops, students proposed implementing a strategy from Cracow Urban Programs on the boulevards at the Stare Dębniki and Salwator. Students also pointed to new ideas, e.g. additional shared cyclist-pedestrian footbridge between Stare Dębniki and Salwator.

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Modern trends in the formation of adaptive architecture

Współczesne kierunki w tworzeniu architektury adaptacyjnej

Abstract

Humans are flexible creatures that adapt their living environment for their own needs. A sedentary lifestyle forced humans to adapt the house building to changeable environmental conditions. Historical adaptable residential buildings were characterized by an increasing range of changes that occurred to the changing needs of occupants. Nowadays, evolving computer technology, intelligent systems and methods of the acquisition of renewable energy influence the growing expectations for residential buildings and their functions. The presented research describes selected contemporary adaptable houses, their features and range of adaptation. The aim is to formulate conclusions about the future of adaptable housing development and its potential. The reflection on this matter is the last part of the article.

Keywords: adaptive architecture, dynamic houses, contemporary residential architecture, flexible architecture

Streszczenie

Człowiek jest istotą od zawsze przystosowującą środowisko mieszkalne na własne potrzeby. Osiadły tryb życia wymusił na człowieku dostosowanie swoich domów do zmiennych warunków środowiskowych. Historyczne domy adaptowalne cechowały się coraz większym zakresem zmian, jakie można wprowadzać w stosunku do potrzeb. Współcześnie rozwijająca się technologia komputerowa, systemów inteligentnych oraz sposoby pozyskiwania energii ze źródeł odnawialnych wpływa na rosnące oczekiwania wobec funkcji budynku mieszkalnego i sposobu jego działania. Przedstawione badania opisują wybrane aktualne realizacje budynków adaptowalnych, ich cel oraz zakres zachodzącej adaptacji. Ma to na celu sformułowanie wniosków związanych z kierunkiem rozwoju architektury mieszkaniowej i potencjałem systemów adaptowalnych które stanowią ostatnią część wywodu.

Słowa kluczowe: architektura adaptacyjna, domy dynamiczne, współczesna architektura mieszkalna, architektura elastyczna

1. Introduction

Adaptable residential buildings and their historical forms were developed by humans in times before our era. According to Robert Kronenburg [9], the term "adaptable" means the built-in ability to adapt to changes in the function, ability of making spatial and functional changes and implementation of a new technology without disturbances within the environment and human life. The ability to adapt plays an important role in improving the comfort of living in the building. One of the first adaptable buildings were Japanese houses. Multifunctional space was achieved by sliding doors (shoji) and sliding panels (fusuma). The house plan consisted of interconnected rooms that could be divided by moving walls in a few seconds.

Adjusting the living space to human needs on the individual level improves the sense of security and well-being, quality of life and can help to maintain family relations on a high level. Adaptability could also bring benefits at the social level. Providing certain possibilities of a house and its configuration achieved without imposing noise and waste to the external environment allows for the proper maintenance of neighborly relations. Adaptable houses can, under certain conditions, benefit future generations – for example – regulations of space privacy between siblings or increasing the usable area for the larger family needs.

In an economic and ecological aspect, an adaptable house fulfills its function better that a traditional house. The possibility of adjusting the space to various stages of life of the residents may allow for a longer operation of the facility, reduce the consumption of materials and use the newest technologies to ensure the best home optimization in relation to environmental conditions. Adaptable processes in a house can provide minimal disturbances in the environment and do not require high financial resources.

The adaptation process can be both simple and complex. The study of a modern approach to the topic of adaptable houses is an essential element for further research of the presented issue. Today, several organizations are characterized by activities in the context of adaptable buildings. One of them is adaptable future[1]. The organization focuses on changing the society's approach to the issue of sustainable construction. Architecture according to Adaptable future should be susceptible to adaptation to the variable reality, becoming also variable. Currently, the group focuses on a research project at the University of Loughborough describing the adaptive abilities of historical buildings and tools that were used at that time. Based on the observations of the changes taking place, the group assumes working out a possible scenario of the future of adaptive construction.

The second institution is the Open Building[2], representing the idea of being "open" to changes in the building. According to the institute, modern times, which are full of technical and social upheavals, require that buildings – by adaptation – remain safe, useful and attractive.

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[1] More about organization "adaptable future" in [13].

[2] More about Open Building institution in [14].

2. Adaptable architecture levels

The typological demarcation of adaptable buildings was introduced by C.M.J.L. Lelieveld [8, pp. 245–252] in the conference article Adaptable architecture. As a general definition of adaptable architecture, Lelieveld adopted the architecture of which specific components can be changed in response to external stimuli (user and / or environment). "Based on the technological advancement levels of individual buildings, the grouping of buildings from the least technologically advanced to those with the most autonomous embedded systems.

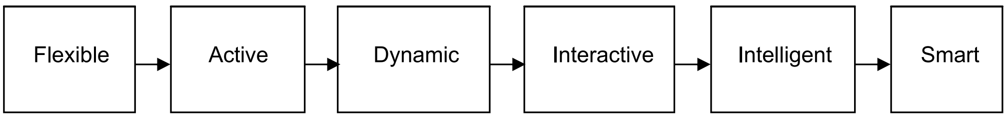

Fig. 1. Adaptation levels in architects adaptable according to C.M.J.L. Lelieveld

Flexible level – The first level in adaptable architecture. Adaptation activities are controlled directly by a human, which means no autonomous actions of the building. Flexible buildings are characterized by the use of common techniques of moving parts: bearings, rails, hinges.

Active level – Individual building components react to the activity of the user or the environment. The operation of the building is based on the action-reaction relationship. The most common example of an active reaction is a light switch. The active level requires the use of electricity in a building that was introduced from the beginning of the 20th century.

Dynamic level – Impacts from the user or the environment causes specific changes in the active components of the building. This is a more advanced level than the active level, because, in addition to action on the action – response relationship, there is a possibility to introduce more options and settings within each component. For dynamic adaptation, use of computer technology is essential. That technology is available for housing since around 1980.

Interactive level – This level is characterized by a bilateral relationship between the building and the user. This technology requires the user's digital detection and undertaking programmed actions related to it. Most often, you can meet interactivity in experimental and demonstration installations placed in cities or tested in laboratories. Currently, intensive research on interactivity is conducted under the direction of Prof. Kas Oosterhuis at the University of Technology in Delft. The group's name is Hyperbody[3]. The group focuses on improving the design techniques, construction and use of interactive architecture, and explores its applications. What is more, group works on interdisciplinary cooperation in digital projects, the implementation of electronic spatial environments and the creation of interactive architecture prototypes.

Intelligent level – The term "intelligent building appeared in the early 1980s. There is no one general definition of intelligent architecture, but the available bibliography offers many similar definitions. The definition of intelligent architecture can be taken from the colliery book by Collier and Thelen [2]. Users experience a system as intelligent not only if it accepts natural language input

[3] More about projects and researches at Hyperbody in [15].

rather than just specific commands, but also if it allows the user to take initiative. If the system adapts itself to the users' interests and interaction preferences and works cooperatively with the user to accomplish specific goals with the use of additional sources of knowledge to meet the needs of the user, a system is considered intelligent" The system is capable of detecting, processing data, makes decisions as to whether to react. The system can take action without user intervention. Intelligent technologies support users in various aspects, such as security, energy saving, information, communication and ensuring comfort (ventilation, heating).

Smart level – Smart buildings have the ability to make changes on their own initiative. The systems of such buildings are integrated with both the life and behavior of users, receive and react to stimuli from the environment and are integrated with each other. In Richard Harper's book Inside the smart home [6], co-author Frances K. Aldrich defines the "smart home" as a "residence equipped with computing and information technology, which anticipated and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through the management of technology within the home and the connections to the world beyond.

3. Criteria and Methods

This study focuses on residential houses characterized by the adaptability of space at the flexible, active and dynamic level. All these three levels introduce physical changes to the object by changing the architectural features of the house, which is discussed in the article. According to Lelieveld's table, there are six adaptive levels. However, the interactive, intelligent and smart level introduce changes to the facility at the technological level, without affecting the building's architecture as the functional layout or extending the usability.

Buildings were searched by bibliography analysis (conference materials, articles, books) in the field of modern "mobile" architecture and the theory of architecture with ambitious computing[4]. Each house collected was analyzed, compared with other buildings, which allowed for a better understanding of the trends and design process of adaptive houses.

4. Residential architecture with a reconfigurable plan

The way of adapting to the needs by creating multifunctional rooms, the possibility of joining zones with each other or sharing them has been used for a long time, starting from Japanese homes and manifesting today in the form of modern homes with various functional configuration options. According to statistical surveys carried out by CENSUS in 2012–2013, the main reason for moving is the desire to change the house for the better and "other reasons related to the house[5]" which suggests the inconvenience associated with the building

[4] Phrase coined by Mark Weiser around 1988. Umbitious computing is a concept in software engineering and computer science where computing is made to appear anytime and everywhere.

[5] CENSUS: *Reasons for Moving 2012 to 2013* [16].

itself. On this basis, it can be concluded that adaptable houses with the possibility of changing the layout of rooms or their size may be more convenient to use and over time become more appropriate by modern families. Below are selected examples of single-family residential architecture belonging to the group of adaptable buildings completed in the 21st century.

4.1. Naked House

The main idea of Naked House was to create a home that provided the maximum amount of common space, in which family members are not separated from each other by private spaces. The house provides everyone with the feeling of freedom so individual activities can be taken in a shared space. Semi-transparent facade of the house thanks to its construction allows a large amount of sunlight brightening the entire internal space. The external walls were made of two sheets of corrugated fiber-reinforced plastics with thermal insulation made of foamed polyethylene. The essence of adaptability in this house is the internal space, freely configurable through movable internal divisions of nylon fabric and wooden modules of bedroom rooms placed on wheels. The additional amount of equipment that can be used in several different ways adds extra freedom. Bedroom areas can be combined to form one large semi-private room, or – just like in Nyborg House – to extend outside the house. The upper cover of the bedroom is an additional space that is used, among other things, to play with children. The whole house is the quintessence of flexible living and is one of a few objects of this type in the world.

Fig. 2. Naked House, Shigeru Ban Architects (source: [25])

4.2. Nyborg Adaptable Houses[6]

The Danish design office Henning Larsen Architects and GXN designed the experimental housing estate in Nyborg with implementation in 2013. The estate includes six detached buildings, each of which was to reduce CO2 emissions during construction and use. These

6 Full information about project in [17].

houses focus on the flexibility of the functional plan and material savings in the event of a reconstruction of the building. The house has an area of 146 m2 and focuses on the changing needs of the family at various stages of life. A growing family, growing up children and changing privacy needs, leaving the house by children, divorce, partner's death. The houses have been designed to adapt functional plans to the needs of users at any stage of their life. In the buildings, load-bearing walls are only external walls. The kitchen can become a room open towards the dining room or living room thanks to the opaque walls. The modular design makes it easy to create an additional entrance to the building.

4.3. Raum transforming house[7]

Another way to transform the functional plan was found by architects from the French Raum studio. The building was designed and built in 2013 for a family with young children in the north-west of France. The building is divided into two parts. The first is a private part, while the second is a semi-private space, accessible from the outside through a large sliding balcony door. The ground floor of the building has an open plan and includes rooms in the living area: living room, kitchen and dining room. Next to the entrance to the house, there are mobile bedroom rooms, which if necessary or in the summer season are moved outside the building. This treatment allows

Fig. 3. Holiday home created by Raum architects. Pic. Audrey Cerdan (source: www.tectonicablog.com, accessed 10.06.2018)

[7] Plans and photos of project in [18].

the owners to increase the surface area of the living space without the need to rebuild or incur costs. The first floor of the building is intended for the main bedroom. Architects took the idea of mobile children's bedrooms from traditional stalls used in the early years in Brittany.

4.4. MJE House[8]

The idea of a multifunctional space and the transformation of a functional plan with sliding and rotating walls is increasingly used in small apartments. The demand for an additional bedroom for accommodating guests, a place in the living area has been implemented so far mainly using folding furniture, but in recent years the number of small apartments with a reconfigurable plan has been increasing. An example is MJE House in Madrid by PKMN architectures. The main assumption of the project was to divide the space of the flat to accommodate the whole family. The apartment uses rotatable – sliding furniture which also comprises partition walls. The space can have an open plan, or it can accommodate two bedrooms depending on the needs of the family.

4.5. The George House[9]

The house has a characteristic construction which is a separate element next to the external walls of the building. The idea of separating the walls from the structure was taken from traditional homes in Samoa. These houses were built using pillars supporting the roof, and the external walls did not have a supporting function. In addition, the walls consisted of blinds that could be raised or lowered as needed.

Architect Richard George assumes that the functional layout of the house should remain independent of the building's construction. The project questions the current traditional layout of residential houses and their permanent, permanent character. Architect's house allows you to change the size of rooms and even reduce their number thanks to the sliding inner walls. The construction of the building is simple and consists of steel poles and beams supporting the roof over the whole. Thanks to this, the outside walls remain non-bearing and consist mainly of glass. In addition, the glass external façade divided into parts can be quickly replaced with an opaque material to create privacy where it is needed. All changes taking place in the building are adjusted manually, quickly and do not require a construction permit.

5. Dynamic adaptable architecture

Dynamic houses are a group of more technologically advanced buildings from previously presented flexible and active buildings. These buildings may have both the ability to transform space and actively respond to changing environmental conditions without interference from human strength.

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8 More information about project in [19].

9 More information about project in [20].

5.1. Sharifi-ha house[10]

A 3-story residential building located in Tehran by Next Office is another example of a dynamic home. The main idea of the building is based just like in the case of D*haus on adapting the building to a large amplitude of external temperatures. An additional factor imposing the nature of the project was the typical dimensions of the plot in Tehran imposing the design of a narrow front facade and a large depth of the building requiring appropriate lighting. The building has three rooms located above each other, which are installed on rotating platforms. Platforms enable the rotation of the room leading to the opening or closing of the building depending on the season, day or for functional reasons. In the summer, the building offers an open internal plan with a large terrace area. However, during the winter season, the building closes, reducing the number of window surfaces, and the terrace area is liquidated for the benefit of the enlarged interior space. The house also adapts to the functional needs of users. Both the guest room as well as the home office and dining room can change the purpose according to the requirements of the residents. The project assumed several scenarios for the functioning of buildings in specific seasons, both functional and in the lighting of rooms.

The house uses simple rotary mechanisms usually used in car showrooms or theaters. Taking into account the specificity of dynamic architecture, it was necessary to remember about dynamically variable ceiling loads and vibrations that could cause deformation of the structure. The construction of the building assumes resistance to the highest possible dynamic loads that may occur during the use of the building and the design process also included SAP2000 analyzes.

Fig. 4. Sharifi-ha house, NextOffice (source: [21])

[10] More information about project in [21].

5.2. Sliding House[11]

London architects from the drMM office designed the world's first completed building in 2009 called the 'sliding house'. The building consists of three separate modules: a proper house, a guest house and a greenhouse. The object has a fourth element, movable in the form of an additional external facade located above the non-modular house modules. The façade moves along the longitudinal axis of the entire complex thanks to the railway rails placed in the concrete platform forming the basis of the entire building and the motors hidden in the thickness of the sliding walls. The mobility of the external façade enables year-round adjustment of the interior lighting and provides additional thermal insulation of selected parts of the building. The object has an internal courtyard and a terrace that can be protected from any precipitation at any time. The design assumption provides for the possibility of extending the ground with traffic lanes for the façade in the event of extending the house with additional functions.

Fig. 5. Sliding house, DRMM architects (source: [22])

Fig. 6. Sliding house, DRMM architects (source: [26])

5.3. A safe house[12]

The penultimate example of a dynamic home was designed by Robert Konieczny from the KWK Promes studio. The building is located near Warsaw, in Poland. The investor's wish was to design a building that would ensure a maximum sense of security, which influenced the use of dynamic systems in the home. The body of the building is perpendicular, combined with a partially movable façade. The house has the ability to "open" to the garden part while creating a closed pre-entering area. This prevents guests from getting into the garden part without going through the house, and children playing will not get out of the house or garden. At night, the mobile walls of the building return to the place, closing the house and providing security for the residents. According to the architect, a safe house is a new type of building with a functional context and is the first of its kind in the world.

In addition to the sliding walls, the building has shutters measuring 3.5 m x 2.8 m opening at a 180-degree angle and a drawbridge connecting the building with the pool pavilion. Another movable element is the rolling gate, which at the same time constitutes the south elevation measuring 14 x 6 meters. All movable elements except the aluminum, roller door

11 Details about project and building in [22].

12 Photos of the building and project description in [23].

have a steel truss structure and are finished with cement-bonded boards. The movement of components is possible due to the installation of electric motors placed in the wall thickness. In addition, the building has recuperation and a hybrid heating system that extracts some energy from the heat pump and solar panels, and some from gas heating. Like the previous examples, the architecture of this house is inspired by natural mechanisms observed in nature - the house operates in a daily cycle, opening during the day, and closing for the night.

5.4. D*Haus concept[13]

An interesting conceptual project awaiting implementation is the D * Haus house project. The idea of the project is based on the concept of the building adapting its form to changing environmental conditions both during the day, as well as during the season or weather conditions. The author of the project is David Ben Grunberg, who originally designed the house based on the atmospheric conditions prevailing in Lapland. The form and operation of the object are based on a mathematical formula that was written by Henry Dudeney. The formula assumes an appropriate division of the square that will enable the rotation of the resulting modules to form an equilateral triangle. The sliding parts of the building are to move on rails placed in the ground, opening the building with glass walls outside during the summer season, accumulating heat inside. In winter or at night, the house is formed to the base of the square, reducing the number of external glazing to a minimum and retaining heat in the interior.

Table 1. List of selected examples of adaptable buildings, its functions and typology

Architect	Name	Place	Year	Process of adaptation	Level
1	2	3	4	5	6
Ban Shigeru	Naked House	Tokyo, Japan	2000	Foldable walls and furniture, by a human	Flexible
Richard George	The George House	Auckland, New Zeeland	2006	Foldable walls, change of room size, regulations of elevation's transparency by changing the panels	Flexible
KWK Promes	Dom bezpieczny	Near Warsaw, Poland	2005–2009	Partially mobile elevation that open and close the house	Dynamic
drMM	Sliding House	Suffolk, Great Britain	2009	Folding external elevation, movable on the rails	Active
Henning Larsen, DXN	Adaptable House	Nyborg, Denmark	2013	Dividing the rooms with sliding walls, a construction allows for quick expansion of the building	Flexible
Thomas Durant, Raum Studio	Transforming House	Brittany, France	2013	Pull-out box bedrooms outside the building	Flexible

[13] Description of the idea in [24].

1	2	3	4	5	6
Nextoffice – Alireza Taghaboni	Sharifi – ha house	Tehran, Iran	2013	Rotating three rooms that regulates the terrace area, lighting and internal temperature	Dynamic
PKMN architectures	MJE House	Salinas, Spain	2014	Folding wall units are dividing the open space	Flexible
David Grunberg	D*Haus	Conception stage	–	The building's form is based on the Haberdasher's formula. Each of the four building's components is rotary and settled on rails	Dynamic

Source: author's study

Table 2. The main goals of the buildings

Naked House in Saitama, Japan	Shigeru Ban Architects	▸ Providing shelter for a 5–person family ▸ The house is to provide the maximum amount of common space and a private minimum „to give everyone the opportunity to take individual actions in a shared atmosphere" ▸ Mobility of small room boxes
The George House, New Zealand	Richard George, Stephenson&Turner architects	▸ Development of an open plan to the building using sliding walls and non–load bearing external walls ▸ Regulation of privacy level
Dom bezpieczny, Warszawa	KWK Promes	▸ The basic assumption was to ensure maximum sense of security for residents
Sliding House, Suffolk, England	DRMM architects	▸ The division of the house zones from semi–private to private ▸ Building a comfortable home for people of retirement age ▸ Diversification of the character of the building depending on the season, weather or preferences of residents using the button
Adaptable House, Nyborg, Denmark	Henning Larsen architects, DXN	▸ Flexibility of the functional plan adapting to the needs of families at every stage of life ▸ Reduction of CO_2 emissions
Transforming House, Brittany, France	Thomas Durant, Raum Studio	▸ Possibility to enlarge the living space in a small building
Sharifi-ha House, Tehran, Iran	Nextoffice	▸ Active regulation of the lighting of the building with narrow elevations ▸ Active temperature control due to the high temperature amplitude in Iran
MJE House, Salinas, Spain	PKMN architectures	▸ The apartment was to be a residence for both a couple of people and for the whole family at the same time
D*Haus	The D*Haus company	▸ The purpose of the building is to adapt the body to extreme outdoor temperatures

Source: author's study

6. Desire to create an ideal home: conclusions

There is no doubt that the development of materials and technology has a significant impact on the increasingly frequent implementation of intelligent components for the building. The presented table indicates the presence of adaptable houses around the world, but also shows a wide variety of ways of adapting each object. It should be emphasized here that each building is unique, has diverse functional properties, structure and a different home – user relationship. There is no recipe and it should not be for one, ideal, universal house model. Based on the above analyzes of adaptable houses, the following conclusions were deduced:

- To ensure the best functioning of an adaptable house project, it is necessary to maintain and develop cooperation between the construction industry and specialists in the automation and robotics as well as IT industries. Knowledge and cooperation of individual industries is essential for the proper adaptation of adaptable tools that are to be used in the building as well as for creating possible building configurations.
- When designing a building, the architect should pay attention primarily to the occupants' comfort of using the building. The success of adaptive buildings depends primarily on their adaptation to the user. A building that does not provide comfort of use, created mainly for the idea, may not be implemented or not be met with public interest – just like the D * Haus house.
- The building should have adaptive abilities that are applicable at several stages of use over a longer period of time. For example, the variable size of rooms within a building should be available at all times, but also the possibility of expanding the usable floor space should be taken into account. The elevation should be constructed in such a way that creating an additional external entrance to the building would not be a problem.
- Adaptation should be easy to achieve. It should take place in a short period of time and does not constitute complicated activities, if they are to be performed by the user. Adaptation requiring a complicated series of commands should be adjusted by a computer to a single user command.
- Adaptation process requiring the operation of automatic components should absolutely be able to switch to manual mode. Changes occurring in buildings often raise doubts both in terms of human security and the preference for independent decision-making about changes. This applies mainly to cyclical changes such as: changing the interior lighting, or automatically adjusting the temperature inside the building.
- For economic reasons, we should look for adaptable solutions that will be the simplest in both design and replacement or maintenance. The largest group of adaptable buildings being constructed are flexible houses. The solutions used in them are not expensive to build and are characterized by the least costly operation and low failure rate. As a result, adaptable buildings will be available to the majority of society with an average material status.

The rapid development of technologies in the field of kinetic systems and the use of energy from renewable sources has opened up possibilities leading to the partial autonomy of buildings and related experiments. In spite of the really small number of adapted adaptable houses, it can be concluded that the most objects are located in the group of flexible objects. Regulating the functional plan is the simplest to achieve without the involvement of advanced technologies and large financial outlays. Houses reacting actively to changing external conditions are treated separately. The interest in ecology and the change of building regulations in the field of zero energy construction can contribute to the increase in the use of intelligent systems in homes, which, in combination with a flexible functional plan, can in practice mean the development of dynamic construction. An increase in the tendency to create semi-autonomous buildings should be expected, aimed at the best possible adaptation to the user with simultaneous broadly understood building optimization.

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A flexible system for localised sustainable development

Elastyczny system lokalnego rozwoju zrównoważonego

Abstract

Responding to population growth requires efficient planning procedures in order to address the challenges of housing demand and consumption of natural resources. Following the decentralised government approach of Germany and learning from past experiences, the city of Frankfurt am Main has adopted a strategic decentralised planning approach that allows the municipality to manage urban development in accordance with the current needs of the city in a specific moment in time. This approach is based on a land use regulation set up by the regional authority, combined with demand-driven localised sustainable development planning on the municipal level. This paper describes the main issues for sustainable urban development in Frankfurt am Main as well as the main characteristics of the spatial planning system, including the planning instruments for localised sustainable planning, non-formalised planning processes and an example of local district planning.

Keywords: sustainable development, flexible planning, strategic planning

Streszczenie

Reagowanie na wzrost liczby ludności wymaga skutecznych procedur planowania w celu sprostania wyzwaniom związanym z popytem na mieszkanie i zużyciem zasobów naturalnych. W związku ze zdecentralizowanym podejściem rządu do Niemiec i wyciąganiem wniosków z przeszłych doświadczeń, miasto Frankfurt nad Menem przyjęło strategiczne podejście do planowania, które pozwala gminie zarządzać rozwojem urbanistycznym zgodnie z aktualnymi potrzebami miasta w określonym momencie. Podejście to opiera się na regulacji użytkowania gruntów ustanowionej przez władze regionalne, w połączeniu z popytowym lokalnym planowaniem zrównoważonego rozwoju na poziomie gminy. Artykuł opisuje główne problemy zrównoważonego rozwoju miast we Frankfurcie nad Menem, a także główne cechy systemu planowania przestrzennego, w tym instrumenty planowania dla lokalnego zrównoważonego planowania, niesformalizowane procesy planowania i przykład planowania lokalnej dzielnicy.

Słowa kluczowe: rozwój zrównoważony, planowanie elastyczne, planowanie strategiczne

1. The Challenges of a Growing City[1]

Located in the federal state of Hesse, Frankfurt am Main is the fifth-largest city in Germany and the heart of the FrankfurtRheinMain metropolitan region with around 5.6 million inhabitants [9, p. 5]. Similar to several other major cities in Germany (and contrary to some shrinking regions in the country), the population in Frankfurt is experiencing a growing trend, as employment and educational facilities, transport connections and good quality of life are continuously attracting new residents. In 2014, Frankfurt reached a population of 708,543 inhabitants, and it is projected to attain around 810,000 inhabitants by 2030 [3, p. 62]. This demographic growth is a trend which is mainly influenced by a population influx from Germany, but also incoming international population employed in the financial, information technologies and chemistry sectors [11, pp. 33–35]. The attractiveness of Frankfurt causes constant demographic and social change, along with a demand for affordable housing, services, infrastructure, and amenities in the city.

A growing city requires a responsive approach to address the emerging issues, while steering urban development towards a sustainable vision of development, in order to increase resilience and minimise the impact on the environment. Frankfurt has improved its position as a city with a good quality of life, where the balance between environmental protection and urban growth is considered a major parameter in the decision-making for urban development. The city is focused on three main urban development aims: avoiding suburban sprawl by a compact, yet green city; promoting social diversity and multicultural lifestyles among the population; and preventing spatial disparities and social segregation. In this sense, the general objective of urban development in the city is to provide attractive and affordable housing accompanied by the provision of good services, efficient urban infrastructure and a high-quality urban environment in order to maintain and improve the quality of life in Frankfurt.

Unlike many other cities, the urban planning system in Frankfurt does not rely on an established city-wide spatial master plan. Instead, the *City Planning Department*[2] and the city *Magistrate*[3] decide step by step on the projects and the areas to be developed in the city by prioritising needs and options of urban development. This system allows the city to react flexibly to emergent challenges and issues, adjust the guidelines of development in accordance with changing urbanisation trends and plan proactively towards an established vision of development. In the next sections, the planning system in Frankfurt will be described, focusing on the urban planning instruments which allow Frankfurt's planning system to be decentralised and flexible while pursuing ambitious sustainable development goals.

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1 This article has been developed in the context of the research project "RAPID PLANNING – Sustainable Infrastructure, Environmental and Resource Management for Highly Dynamic Metropolises" and the related subproject 3 "Urban Planning and Capacity Development" sponsored by the Federal Ministry of Education and Research and under responsibility of under responsibility of the Frankfurt University of Applied Sciences Rapid Planning research team, directed by prof. Dr. Michael Peterek.

2 In German: Stadtplanungsamt.

3 In German: Der Magistrat der Stadt Frankfurt am Main.

Fig. 1. City centre, Frankfurt am Main (©FRA-UAS 2015)

2. The Planning Approach in Frankfurt: Strategic Decentralisation

Understanding Frankfurt's spatial planning system begins with recognising a main characteristic of the German public management approach: decentralisation. Germany has a history of decentralisation that has deeply influenced the urban planning approaches in German cities, too: from the formation of the country as a federal state to the creation of metropolitan regions for supporting sustainable development efforts and the resolution of regional conflicts, but where each municipality has by constitutional law autonomy over the decisions regarding urban development within its municipal limits. Urban development, therefore, could be seen as a reflection of the political history and structuring of Germany [4, 7]. Therefore, although the federal and state levels provide the guiding principles and legal basis for spatial planning, it is at the municipal level that the land uses for urban development are defined and regulated [7]. This autonomy translates to the municipal administrative dynamics, with the municipality allocating diverse urban development responsibilities among the different municipal departments and agencies.

Frankfurt is a relatively compact city and the heart of the polycentric Frankfurt Rhine Main metropolitan region. Although the city is autonomous in defining its own development goals, the provision of urban infrastructure and public services relies on the collaboration with the region. The process of spatial planning is dependent on regional dynamics, as well as the local development trends of the city. In this sense, the city must balance municipal interests with the interests of other municipalities in the region.

3. Preparatory Land Use Plan: Regulations for Coordinated Regional Development

According to the report of the Economic Commission for Europe [21, p. 11], one of the fundamental concepts of spatial planning is the "Subsidiarity Principle". It indicates that decision-making should be driven by local needs and taken at the local level whenever possible. Only when the impact of urban development extends beyond the jurisdiction of a single administration, a higher decision-making level might be necessary. Therefore, regarding a coordinated land use planning and to avoid duplication of functions, Frankfurt is involved as an important player of the *Regional Authority FrankfurtRheinMain*[4], a legally constituted management body that coordinates regional development in the FrankfurtRheinMain region, to cooperate with the region for the formulation of the *Regional Preparatory Land Use Plan*[5].

Fig. 2. Frankfurt's central train station district, connection to the region (©FRA-UAS 2004)

4 In German: Regionalverband FrankfurtRheinMain.

5 In German: Regionaler Flächennutzungsplan.

The existing challenges, such as affordable housing, transport management, public infrastructure provision as well as protection of the environment and ecology, highlight the importance of cooperating with the surrounding cities and municipalities for meeting the needs of a growing region. As the by-far largest city in the region, Frankfurt offers opportunities for employment as well as social and cultural facilities for both locals and commuters. However, Frankfurt also demands natural resources, e.g. energy and water, only available from the surrounding region. Therefore, the existence of the Regional Authority, as the regional body for expressing and responding to inter-municipal challenges and conflicts, is essential for the quality of life for urban dwellers in Frankfurt and its surroundings.

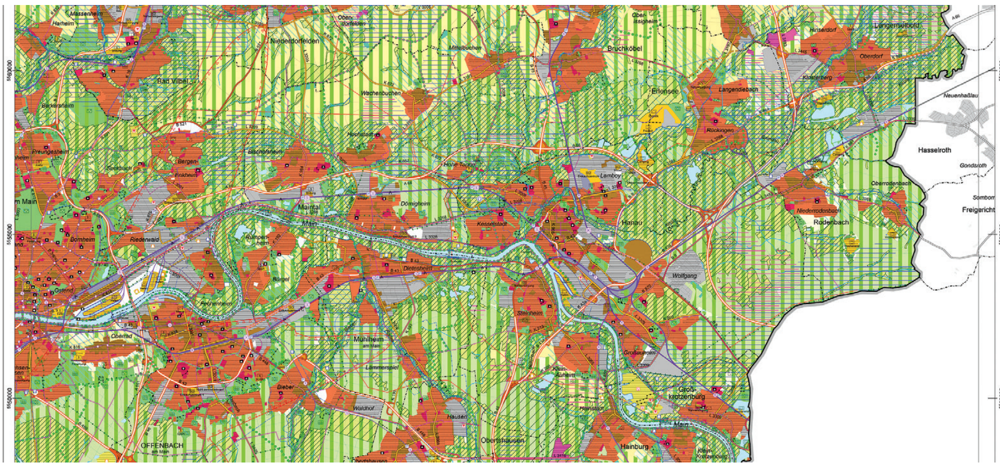

Fig. 3. Section of the Regional Preparatory Land Use Plan – Urbanisation along the river Main, including the eastern part of the city of Frankfurt, and the municipalities of Offenbach, Mühlheim and Maintal (source: Regionalverband Frankfurt Rhein Main 2016)

In response to the cooperation needs, and as a measure to balance the interests of the cities and municipalities in the region, the state of Hesse established by law the FrankfurtRheinMain Region, today composed by 75 cities and municipalities located in the south of the state. This formally established region (which is smaller than the even more extended metropolitan region) accommodates 2.3 million inhabitants (in 2016) and it is managed by the Regional Authority Frankfurt Rhein Main [6].

The Regional Authority through its legal base has the ability to decide on all land uses allocation in its territory through the *Regional Preparatory Land Use Plan*. This plan provides a framework for city planning and urban, environmental and infrastructure development and aligns local policies and development goals with the needs and vision for the region for each city and municipality associated to the Regional Authority. The plan is meant to empower municipalities to meet the challenges of urbanisation and environmental protection and pave the way for further localised planning procedures [4, p. 2; 17].

For Frankfurt, the need to collaborate with the region has resulted in the definition of a two-stage planning process, guided by the urban development goals and strategies established by the municipality. The first stage is based on the Regional Preparatory Land Use Plan established by the Regional Authority [8, p. 6]. The second stage is based on localised decision-making and planning, carried out by the Magistrate and the City Planning Department in Frankfurt respectively. The regional planning stage defines the land uses in a regional scale from a strategic perspective, while the local planning stage defines the urban development vision, objectives and strategies through a set of diverse urban planning instruments to regulate localised urban development.

4. Local Urban Development without a Master Plan

Urban development in cities with a rapid population growth is influenced by diverse and sometimes unpredictable factors. Many cities around the world have adopted a spatial master plan approach to define land uses, densities, green areas, among other functions on a city-wide scale. These master plans are useful planning instruments to integrate urban sectors and outline the future urban development of the city for the next 12-20 years [2]. These plans produce a legal regulations framework to steer urban development towards the specific objectives defined by a city. The framework is defined by addressing the urban needs and the political orientation of the government. The master plan itself is a snapshot of the city in a particular moment and due to the rigidity of the legal framework, it often lacks the ability to adjust to the emergent challenges of urbanisation.

The master plan approach may present a feasible development strategy for cities with a stable or slow population growth and where globalisation or external forces have almost no direct impact on the urban development. However, for highly dynamic cities in which the demographics change rapidly, e.g. in the developing world, or globalised cities with the burden of accommodating a growing international population while balancing local needs, environmental concerns and economic pressures, an inflexible master plan approach falls short in its possibilities to modify existing regulation or to address unexpected changes. The experience of Frankfurt as a global city with a flexible localised planning process brings into question the effectiveness of a city-wide master plan approach, because a centralised, detailed, long-term master plan, produced as a spatial projection of the future at a specific moment in time, could probably not adequately steer the urban development in a dynamic growing city susceptible to the pressures of rapid demographic and economic change.

The spatial planning system in Frankfurt breaks down the master plan approach into a system of smaller-scale and more specific plans. The strategic and comparatively flexible scale of the *Regional Preparatory Land Use Plan*, mentioned above, leaves the more rigid detailing to localised plans aimed at the development of limited areas of the city with a greater need for regulation. The main local planning instruments in Frankfurt could thereby be classified into three categories, regarding their legal basis [16]: measures and bylaws of the Federal Building Code; bylaws of the State Building Code; and Legal Site Planning. These instruments are mostly incorporated into a specific *Legal Zoning Plan*[6] for each area under

[6] In German: Bebauungsplan.

development, which is drafted and projected by the City Planning Department. The legal zoning plans produce detailed legally binding regulations and specifications steering urban development towards the objectives of the city.

For developers, investors and individuals, legal zoning plans are the key to securing building permissions. The admissibility of a project can then be decided on the basis of a qualified legal zoning plan [3]. A wide range of further specifications and possible contents in the legal zoning plans are allowed according to the Federal Building Code [1, 4, 7, 14].

4.1. Urban Development Measures and Urban Refurbishment Measures[7]

The Federal Building Code provides a set of measures to generate a legal framework for projects which fall outside the existing regulations for land uses and development. These measures can also complement the function of legal zoning plans as well as facilitate and control their implementation. They allow the swift acquisition of previously unused land, vacant land, or land required by the municipality for essential urban development purposes. They can also legalise construction in previously non-developable land under specific circumstances and allow the financing of municipal development projects.

For the urban development measures to be implemented, an urgent need for development, e.g. for housing provision, must be present, along with the feasibility of swift implementation, acquisition of property by the municipality and availability of finances. The municipality has then the right to acquire land for future developments at a price not yet influenced by the real estate speculation. The City Planning Department develops a potential development plan and the city sells the plots at the higher price of the developed building plots. All costs occasioned by the measure are financed by the differential between the purchase value of the land and the market value after the development plan is drafted. The capital surplus from the land sale has to be reinvested into the public and the social infrastructure, parks, and greeneries.

When there are shortcomings in the urban fabric, refurbishment measures for urban development can be initiated by the municipality. An urban refurbishment measure is an instrument that comes under the special building laws covering the urban renewal of entire districts; an urban refurbishment measure also aims at executing the project within a specific period of time. The City Planning Department underlines two indicators for shortcomings representing a need for refurbishment measures: if the area falls short in fulfilling the general health and safety conditions for the people living and working in the area, or if the area is considerably hindered to fulfill the functions given by its location and uses [20]. The refurbishment measure is an enforcement order, it is mandatory for owners and it is their responsibility to undertake a refurbishment building measure [7]. These include in particular the construction of new or substitute buildings, overhaul and relocation of companies and if necessary changes to the firms' operations [20].

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[7] In German: Städtebauliche Entwicklungsmaßnahme; städtebauliche Sanierungsmaßnahme.

4.2. Preservation and Design Bylaws

In contrast to the urban development measures, preservation bylaws enable the municipality to discourage urbanisation, refurbishment or redevelopment, and preserve the specific urban character of an area. The common purpose of the preservation bylaws is to protect the visual quality of the area, the aesthetic value of a landscape or other physical structures and elements of outstanding historical or artistic importance. Bylaws are also used to maintain the social composition of the local residential population and their social milieu as an instrument to prevent gentrification in an inner-city residential area, or to support and reorganise the structure of urban areas in a manner that is socially equitable [7, 18]. Preservation bylaws do not stipulate any specific design regulations but can designate specific areas within a legal zoning plan as preservation areas, where the dismantling or demolition of structures, alterations or changes in the land uses require a special permission. In the case of a preservation bylaw, also all other building activities that do not usually require building permissions are compelled to ask for a special permission [7, 18].

Similarly to the preservation bylaws and based on the State Building Code, the City Planning Department in Frankfurt utilises design bylaws in order to ensure the architectural quality of structures. They stipulate the design framework that new buildings must follow, and regulate the exterior design, e.g. the shape of the roof, the materials used etc., landscape and advertisement space. On the contrary to a preservation bylaw, the design bylaw makes precise stipulations with regard to the design of structures that are in the interest of a harmonious urban and architectural overall appearance. They can take the form of an independent bylaw, or also be integrated into the legal zoning plans [12].

5. Legal Site Planning[8]: A Flexible Planning Process

When referring to the concept of flexibility in spatial planning, the report of the Economic Commission for Europe [21], highlights the "Principle of Proportionality". This principle states that although the presence of strong regulations in urban planning contributes to creating stability in the city and control over the utilisation of non-renewable resources, a certain degree of flexibility is necessary to address the emerging economic, social and technological issues. This proportionality principle contributes to determining the degree to which a specific pre-existing regulation would be introduced in the formulation of an official urban development plan. Flexibility stimulates new initiatives and innovation, focusing on the desired outcomes. Furthermore, the unpredictability of some urban issues requires flexible policies in order to allow planners to prioritise and focus their attention on the emergent issues, meeting the needs of a particular situation in a more effective way.

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8 In German: Bauleitplanung.

Fig. 4. European Central Bank and Osthafen skaters park (photo by M. Peterek 2015)

In the case of the city of Frankfurt, legal site planning illustrates the principle of proportionality by avoiding the establishment of a rigid city-wide legal framework, and looking instead at the individual needs of different areas of the city, prioritising localised development projects in accordance with the urban vision. Legal site planning aims at steering urban development towards sustainable and balanced land uses by providing the instruments for integrated planning [13]; it is a form of land use planning that defines regulations regarding lot coverage, building heights, densities, obligations for public spaces, special housing typologies and other requirements, confined to a defined area of the city [7].

5.1. Legal Zoning Plans

The results of the legal site planning process are the legal zoning plans, which reflect the utilisation of the principle of proportionality in the planning system in Frankfurt. The City Planning Department is under no obligation to produce a city-wide master plan or legal zoning plans for the entire municipality [14]. Therefore, legal zoning plans are only developed for areas where it is considered necessary for urban development, allowing the city to focus and prioritise its efforts on finding solutions for more pressing urban issues in specific areas. The discretionary nature of the City Planning Department avoids spending unnecessary time and resources in the development of legal zoning plans for areas with no particular needs, increasing the efficiency of the municipality work.

Fig. 5. Ostend district (photo by M. Peterek 2015)

The legal zoning plans define detailed legally binding regulations on a scale that usually ranges from 1:500 to 1:2,000, following the legal framework of the Regional Preparatory Land Use Plan established by the Regional Authority. The legal zoning plans are adopted by the City Parliament in the form of a bylaw or municipal statute, and constitute the basis for other development activities and measures needed to implement the Federal Building Code, including land reallocation, land improvement, provision of local public infrastructure, compensation, expropriation, urban development enforcement orders, etc. [1, 4, 7, 14].

5.2. Non-formalised Planning

Another example of flexibility in the planning system in Frankfurt is the possibility of stakeholders, internal and external to the municipal departments, e.g. property owners, community organisations, developers, investors, etc., to initiate and propose localised urban development projects. Plans proposed by external actors are part of a *non-formalised planning*[9] process in Frankfurt, which complements the aforementioned formal planning instruments, giving the municipality a broader perspective of the real estate market and urbanisation trends in the city.

9 In German: "Informelle Planung". This term does no refer to informality in the sense of illegality, but a project proposal that is not part of the formal planning process.

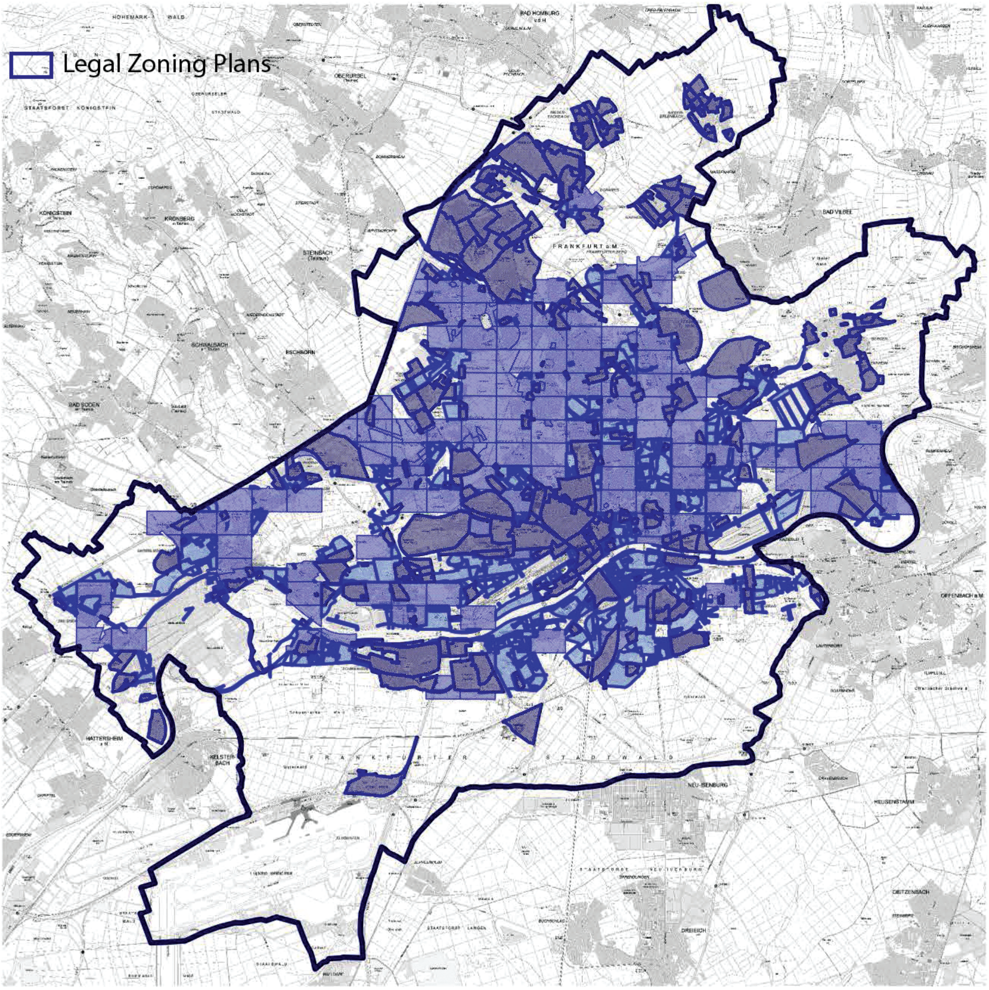

Fig. 6. Overview of existing legal zoning plans in Frankfurt am Main
(source: Stadtplanungsamt Frankfurt am Main 2017d)

In the non-formalised planning process, the stakeholders draft development plans as proposals, which are later to be studied by the municipality in order to decide whether the projects would benefit urban development in the city. This discretionary character of the municipality motivates the private sector to propose innovative development projects, as well as inclusive discussions about a wide spectrum of urban issues. The non-formalised planning process may subsequently go through the scrutiny and formalisation process in the same way a legal zoning plan is analysed and sanctioned by the City Planning Department, the Magistrate and the City Parliament; if accepted it will become a legal zoning plan legally binding to be developed in the city. Examples of at the beginning non-formalised planning processes include the development of the *Westhafen* and the *Europaviertel* districts.

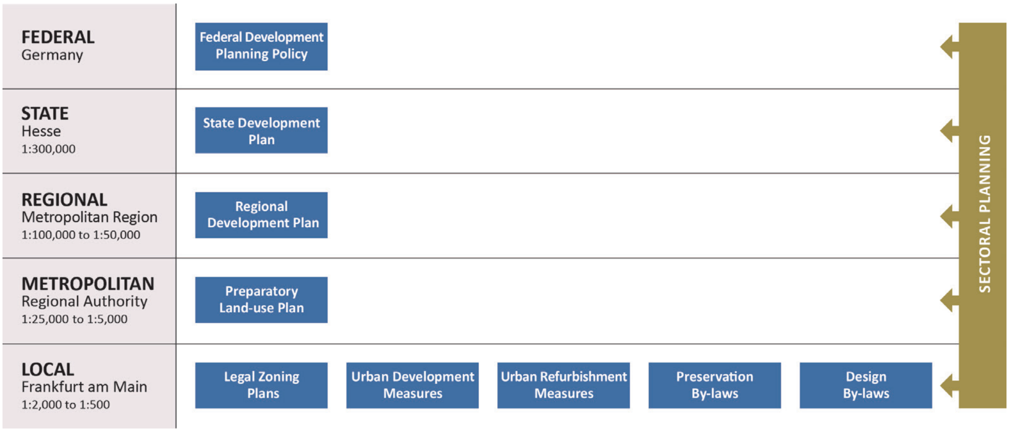

Fig. 7. The formal instruments of the urban planning process in Frankfurt and the RheinMain region. Elaborated by the Rapid Planning research team of FRA-UAS (based on [7, pp. 39, 41, 69–86; 16]

5.3. Example: Riedberg District

As a response to the increasing housing demand that was already present in Frankfurt from the early 1990´s, in 1996 the Magistrate considered it necessary to formulate an urban development measure. This instrument allowed the city to acquire 267 hectares of agricultural land located on the northwest limits of Frankfurt. The city acquired the lands at a price not yet influenced by the real estate market speculations, and was able to sell the newly developed plots at a higher price. The capital gain resulting from the plot sell was invested in financing the infrastructure development of the area, social facilities, urban and transport infrastructure and open spaces [19].

The Riedberg development is currently one of the largest urban development projects in Germany. The implementation started in 1997, and it is divided into 94 hectares for parks, greeneries and landscaping; 89 hectares for construction land; 45 hectares for mobility infrastructure, streets and public spaces; 17 hectares for communal facilities, social services and sports facilities; and 22 hectares for the Natural Sciences Faculty of Frankfurt's Goethe University. The district comprises seven different quarters, each one with its own legal zoning plan. Once it will be completed, it is expected to accommodate a lively mixed-use development with approximately 15,000 inhabitants with a diversity of incomes, accommodated in around 6,000 diverse dwelling typologies. The development also plans for the provision of 3,000 jobs, as well as a community of around 8,000 students. Commercial and recreational facilities are also in the plan and offer different shopping opportunities and public amenities just 20 minutes away from the Frankfurt city centre [19].

Riedberg is a district in which diversity of uses, activities and socio-demographic structures have been considered since the early design phases, to offer a variety of opportunities and options within the same area to create an active community. In terms of education facilities, it offers kindergartens, day-care centres, elementary and middle schools, the Natural Sciences Faculty of Frankfurt's Goethe University and even some postgraduate studies. There is an attractive commercial district with different shops and restaurants. A family centre and the several events

Fig. 8. Housing at Riedberg district (photo by M. Peterek 2011)

organised throughout the year also provide different leisure and cultural opportunities, creating a lively district [5]. As part of the general open space strategy, over one third of the total area of the district was destined to the creation of a network of parks, plazas, green trails and other landscaped areas not only for leisure activities, but also for environmental and climatic purposes, including open water retention areas in the Kätcheslachpark and the Bonifatiuspark [5, pp. 23, 24].

6. Conclusion

In Frankfurt, there is a well-defined planning structure, instruments, and procedures working in parallel with a clear approach towards a decentralised municipal administration, both based on a relatively long history of planning practice influenced by the legal system. The city has a flexible and decentralised planning system, able to maintain a healthy interaction for the provision of public services and coordinated infrastructure with the region. The large-scale, long-term Regional Land Use Plan is drafted by the Regional Authority with the strategic purpose to guide regional development and avoid conflicts between its 75 member municipalities. Nevertheless, the autonomy of the municipalities in the formulation of their respective vision, objectives, and utilisation of the appropriate planning instruments is not diminished by the regional mandate.

Fig. 9. Riedberg development plan (©HA Stadtentwicklungsgesellschaft mbH, 2003)

The city of Frankfurt exhibits extensive experience and capabilities in the implementation of diverse planning instruments for the achievement of its ambitious sustainable development objectives. The choices made by the municipality in avoiding a city-wide spatial master plan approach and implementing a more flexible and localised planning process responds effectively to the pressures imposed by globalisation, internationalisation of the economy and urban growth pressures. By breaking down the master plan approach into smaller-scale and more detailed legal zoning plans, and adopting a prioritising discretionary position regarding development projects, Frankfurt´s spatial planning system has become a flexible system which allows the adaptation of the city to unpredicted urbanisation challenges.

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How Do They See Us from Afar: British Scholars and Romanesque and Gothic Architecture in Lesser Poland

Jak widzą nas z daleka: brytyjscy uczeni a romańska i gotycka architektura w Małopolsce

Abstract

Romanesque and Gothic architecture in Poland cannot compete with European medieval masterpieces even though before the 15th century, medieval buildings in the Kingdom were created by foreign master-masons who came from far afield. Until recently, Gothic and especially Romanesque churches did not attract attention of British scholars. It is now rewarding for the Polish reader, that thanks to Paul Crossley, Alexandra Gajewski, Zoë Opačić, Agnieszka Sadraei and primarily Eric Fernie, Polish medieval architecture appears for the first time in international literature. Encouragingly, even if it has been created on the outskirts of the Latin culture, it is now seen as being closely anchored in the European artistic ***universum*** of that time.

Keywords: Lesser Poland, Medieval architecture, British scholars,

Streszczenie

Romańska i gotycka architektura w Polsce nie może pretendować do najwybitniejszych realizacji europejskich. Należy też pamiętać, iż aż do wieku XV wieku średniowieczne budowle wznosili u nas muratorzy obcy, którzy przybyli z Italii z Węgier lub krajów Cesarstwa. Do niedawna nasze kościoły gotyckie, a zwłaszcza romańskie, nie przyciągały uwagi brytyjskich naukowców. Dla polskiego czytelnika satysfakcjonujące jest to, że od kilku lat dzięki Paulowi Crossleyowi, Alexandrze Gajewski, Zoë Opačić, Agnieszce Sadrei, ale przede wszystkim dzięki Ericowi Ferniemu, polska średniowieczna architektura po raz pierwszy pojawiła się w międzynarodowej literaturze naukowej w całej swej prowincjonalnej okazałości, lecz ściśle związana z artystycznym ***universum*** ówczesnej Europy.

Słowa kluczowe: małopolska, architektura średniowiecza, naukowcy brytyjscy

Romanesque and Gothic architecture in Poland cannot compete with the medieval European architectural masterpieces, which inspired and documented the stylistic evolution in the Middle Ages. The universalism of these transformations can be clearly traced across Europe, from the Iberian Peninsula to the eastern limits of Latin civilization. It was through Poland that the eastern boundaries of the Romanesque style extended running from Gdansk through Kałdus, Płock, Czerwińsk, Szczebrzeszyn to Przemyśl. The borders of Gothic style stretched even further to the east - from Lithuania into the Ruthenian lands (Latyczów). Built on the outskirts these were not foundations of provincial quality because they were created by foreign master-masons who came from far afield. Some of them have been hypothetically identified, for instance the construction of the Romanesque monastery church in Czerwińsk, probably involved craftsmen from the Italian workshop of Viligelmo de Modena [9; 10, pp. 215–226]. Foreign masters, such as Nikolas Werner from Prague and Hungarians from Zips/Spiš (Johann Csipser, among others) contributed to the construction of the large, 14th-century Gothic basilicas in the capital city of Krakow [eg. 15]. It was not until the mid-15th century that Polish-sounding surnames (Marcin Proszko) appeared in the accounts of the construction of churches near Krakow founded by Jan Długosz, a Canon of the cathedral and a distinguished historiographer. Despite geographical distance from the most important artistic centres, the cathedrals, monasteries and parish churches erected in Poland faithfully reproduced the spatial arrangements, the stylistic character and the architectural detail

Fig. 1. Krakow, cathedral church, Gothic west front (photo by P. Guzik, after [16])

typical of their European counterparts. The only provincial aspects were: diminished size, some simplifications and a small number of such buildings.

In both Romanesque and Gothic periods, the richest and most densely populated Lesser Poland with its capital in Krakow was distinguished from other provinces of the kingdom. This is where the building stock was at its most abundant and impressive, at the same time displaying a multitude of artistic influences and trends that are well-recognized by modern art historians. No wonder that the spectacular Gothic projects from the time of the reign of King Kazimir the Great in Poland attracted the attention of Prof. Paul Crossley. Exactly 45 years ago in 1973, he defended his doctoral thesis written under the supervision of Prof. Peter Kidson at the Courtauld Institute of Art in London. The title was The *Architecture of Kazimir the Great*. Twelve years later, his book, featuring a Polish summary, was published in Poland by the publishing house of the Royal Castle in Wawel [3][1]. Crossley's work was an important and major breakthrough in our state of knowledge, and methodological approach to the so-called "King Kazimir architecture". Even though only a young scholar, Crossley delivered a model analysis of Kazimir's foundations, identified and defined the stylistic phases of Krakow cathedral linking them to stylistic changes in Central Europe, and providing relevant and illuminating comparative material. He mapped out the place of 14th-century Krakow in the evolution of European architecture from the Classical into Late Gothic style. In his research, Crossley focused on Krakow cathedral as formally and ideologically a most complete Polish royal foundation. It was a real *Königskirche*, which beside functioning as an episcopal seat, became also a coronation church and the royal necropolis. Crossley devoted an extensive chapter to the unique presbytery of St Mary's church, the first so-called *Hochchor* in Lesser Poland. It must be emphasized that, even though the formal inspirations for the interior layout came from Upper Rhineland, it was in Central Europe that the *Hochchor* type reached the greatest height: 30–33 m in Prague churches and 24-28m in Krakow ones.

As already a widely-recognized professor of the Courtauld Institute of Art and a member of the British Academy[2], Crossley continued his research on Polish monuments, primarily Krakow cathedral, concentrating on its ideological content as *Königskirche* [2, pp. 49–68; 4, pp. 31–45]. He also encouraged his students to work on Polish Gothic [12[3]; 14, pp. 83–116] and inspired Polish researchers with his modern analyses [16].

In 2011 Prof. Paul Crossley and Dr Agnieszka Sadraei were instrumental in organising the annual conference of the British Archaeological Association in Krakow on the subject of "Medieval Art, Architecture and Archaeology in Krakow and Lesser Poland" [13]. The conference brought together Polish and international scholars and the local audience had an opportunity to listen to several papers by British scholars including Prof Crossley himself,

1 Young readers should be made aware that in communist Poland it was standard to take so long to publish a book. To publish a paper in an academic journal took approximately three years.

2 Professor Paul Crossley FBA, FSA, for many years he lectured at the Courtauld Institute of Art in London and later he was also a Slade Professor of the Trinity College at Cambridge University.

3 Dr Agnieszka Roznowska-Sadraei BA, MA, MSc, PhD – worked for several years as Properties Curator for English Heritage and has recently taken up the post with Historic Royal Palaces as Buildings Curator at the Tower of London.

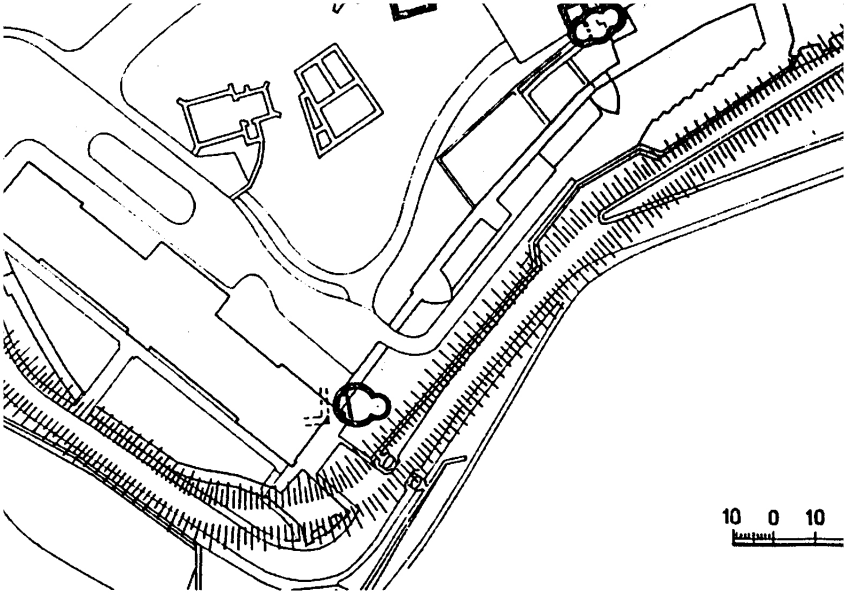

Fig. 2. Krakow, Romanesque churches on the cathedral hill in the middle of the 12th c. (source: [16])

as well as Dr. Zoë Opačić[4], Dr. Aleksandra Gajewski[5] and, above all, Professor Eric Fernie, a member of the British Academy, and a world-renowned expert in Romanesque architecture[6].

Paul Crossley had a truly erudite introductory lecture. Zoë Opačić developed Paul Crossley's insights on the relations of architecture and liturgical ceremonies in the cathedral churches of Krakow and Prague [11, pp. 95–117]. Alexandra Gajewski, according to her specialization, focused on Cistercian monasteries in Lesser Poland [7, pp. 175–197; 8, pp. 212–217]. But in the context of this review it is Eric Fernie's paper on St Andrew's church in Krakow that deserves special attention.

This church is an impressive, if somewhat puzzling foundation and has not been thoroughly studied and investigated, and research conclusions on various aspects of its architecture have been controversial. A unique transept basilica, it has a nave reduced to one bay, and its *Westwerk* was added later and built into the next bay to the west. Fernie found examples of other basilicas with a short nave and argued that their territorial dispersal in Europe cannot be considered as simply coincidental because of close interrelations within the Latin Church. This

4 Dr Zoë Opačić BA, MA, PhD, FSA, is a Senior Lecturer in the History and Theory of Architecture, at the Department of History of Art of the Birkbeck College, University of London. She is also an Editor of the 'Journal of the British Archaeological Association'.

5 Dr Aleksandra Gajewski PhD, FSA is the specialist in mediaeval architecture. She has lectured at the Courtauld Institute of Art, at Birkbeck College, at the Victoria & Albert Museum, and as Visiting Assistant Professor at the University of Michigan, Ann Arbor. She has just completed a European project at the Centro de Ciencias Humanas y Sociales in Madrid as a Senior Researcher. She has published widely on the Cistercian architecture in France, the Holy Roman Empire and Bohemia. She is also the Reviews Editor in 'The Burlington Magazine'.

6 Professor Eric Fernie CBE, FRSE, FBA, FSA is a famous Scottish art historian. He was the Director of the Courtauld Institute of Art (1995–2003) and the President of the Society of Antiquaries of London (2004–2007).

seems especially insightful because in the Polish kingdom (even in Krakow) and especially in the Romanesque period, not only masons but above all the clergy, including the majority of the Episcopate, were mostly foreigners. Perhaps for this reason the architecture created on the borders of Latin *christianitas*, grew out of and was firmly anchored in an international context. In the local comparative context, Fernie pointed to a group of Romanesque small, single -nave churches erected in Lesser Poland in the 12th century, and distinguished two of them – in Jędrzejów and Prandocin, due to their planform featuring a double apse. Therefore, paradoxically, it is not the Romanesque cathedral basilicas, but humble churches of Lesser Poland together with St Andrew's, a reduced basilica that first made appearance in British and, simultaneously, international scholarship [6, pp. 17–27].

Soon Fernie's fascination with Polish and Central European Romanesque bore fruit in the shape of a monumental volume and a comprehensive academic compendium published in 2014 [5]. It successfully replaced the earlier one written by Kenneth J. Conant and published in the same Pelican History of Art series [1]. In this publication Fernie adopted an innovative methodological approach reflected in the layout of the chapters, which combine problematic issues - definition of style (chapter: *Definitions*), types of buildings (chapter: *Themes*), methods of analysis (chapter: *Methods*) as well as chronology (chapters: *Early, Middle and Late phases*) and topography (chapters on the Empire, regions of France, Italy, Iberian Peninsula, British Isles, Central Europe and Scandinavia). He also devoted a few extensive sections to Poland and it should be emphasized that this is the first review of Polish Romanesque monuments on an international forum. Furthermore, the narrative is complete with an indispensable and concise historical introduction explaining to English-speaking readers the circumstances of the reception of Christianity by Polish rulers at the end of the 10th century and establishment of the independent Polish church metropolis in 1000 during the visit of Emperor Otto III in Gniezno (Greater Poland). Such an introduction is important as a focus on the time when the first masonry buildings were constructed in the kingdom. Amongst these buildings, palaces with chapels at Ostrów Lednicki (Poznan), in Giecz, and later in Wiślica deserve special mention. The first and earliest of these palaces includes a building with baptismal fonts in the pavement. Fernie thinks that the Polish phenomenon of palace complexes with baptisteries buildings could have inspired the patrons in the Empire and quotes Galliano near Como as an analogy for the unique baptistery at Ostrów Lednicki, even though the Lombardain example is a slightly later foundation. In turn, he juxtaposes the complex of round churches on the cathedral hill in Krakow with Moravian rotundas and argues that they all may have a common source in the Ottonian Empire, to the North or South of the Alps. Fernie's analysis of these pre-Romanesque buildings is the more impressive since they survive mostly as mere remnants of foundations or lower walls. While discussing palatial types of those well-preserved monuments, which can be thoroughly investigated, Fernie draws attention to different artistic influences in the southern (the Lesser Poland province) and northern (Greater Poland province) parts of the Polish kingdom: the Meuse Valley region inspired Greater Poland, while Upper Rhineland and Alsace – Lesser Poland via Bohemia. Therefore, the double apse basilicas, such as the cathedral church in Krakow (before 1079 to 1142) and the collegiate church in Tum (Middle Poland, c. 1136–1161) repeated the planform of the cathedral church in Prague (1060–1096). Their primary model was the cathedral church in Mainz, the archdiocese of Prague. The surprising influences from Upper Rhineland are noticeable even in the ornamentation of the arcades of the portal and windows in the small church in Prandocin. These resemble ornamentation details in the monumental cathedral in Speyer. The closest parallels for the collegiate church in Opatów can be found in Alsace. In turn, the Benedictine church in Mogilno in Greater Poland has close analogies with churches in the Meuse Valley, in Celles and Hastieres. Taking all this into account Fernie aptly concludes: „Despite Poland having remained independent while Bohemia became a duchy of Empire, the types of buildings and evident changes are remarkably similar in the two centuries" [5, p. 167]. He therefore reiterates the conclusion from his previous publication, namely that provincial architecture at the eastern boundaries of *christianitas* grew out of international context.

Fig. 3. Krakow, St Andrew's colegiate church and a model of the Krakow's borough in the middle of the 13th c. (Reconstruction by Marcin Orkisz MM Interactive after [6])

Apart from the above considerations, in other chapters Fernie cites many Polish pre-Romanesque and Romanesque churches from outside Lesser Poland: Strzelno, Tum. He also draws attention to the sculptural decorations of Polish churches and in Lesser Poland the most prominent for him is Kościelec Proszowicki.

It should be emphasized that the author is well versed in the historical material and in Polish-language literature, which he introduces to international scholarly literature. It is rewarding for Polish readers that thanks to Professor Fernie, Polish pre-Romanesque and Romanesque architecture appears for the first time in English-speaking literature. It may have been created on the outskirts of the western empire but is certainly closely related to the artistic *universum* of Romanesque Europe. As the subtitle of the book indicates, the Romanesque was the first universal style connecting the vast and distant regions of Latin Europe.

Fig. 4. Prandocin parochial church, an ornament on the portal arcade of the 12th c. (photo by S. Dziuba)

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Flame retardants of polymeric materials – calculation of the oxygen index

Antypireny materiałów polimerowych – obliczenia indeksu tlenowego

Abstract

This work presents problems associated with the flammability of polymeric materials which are widely used in many industries (PP, PE, PVC, PS, PET). The first part of the article discusses and characterises the methods of flame retarding polymeric materials, through their modification with a suitably selected fire retardant. The second part of the work presents the possibility of assessing the flammability of polymer materials, without performing laboratory tests, using the oxygen index method (*OI*). A two Johnson equations and the van Krevelen equation were used in the calculations. The strongest agreement between the results of *OI* and experimental values was obtained from the Johnson equation for PE and PP, and for PS from the van Krevelen equation.

Keywords: polymeric materials, flame retardants, oxygen index

Streszczenie

W pracy przedstawiono problematykę związaną z palnością materiałów polimerowych, powszechnie stosowanych w wielu gałęziach przemysłu (PP, PE, PVC, PS, PET). W pierwszej części artykułu omówiono i scharakteryzowano sposoby zmniejszania palności materiałów polimerowych, poprzez ich modyfikację odpowiednio dobranym antypirenem. W drugiej części przedstawiono możliwość oceny palności tworzyw polimerowych, bez wykonywania badań laboratoryjnych, za pomocą metody indeksu tlenowego (*OI*). W obliczeniach wykorzystano dwa równania Johnsona oraz równanie van Krevelena. Największą zgodność wyników *OI* z wartościami eksperymentalnymi otrzymano z równania Johnsona dla PE i PP, a dla PS z równania van Krevelena.

Słowa kluczowe: materiały polimerowe, antypireny, indeks tlenowy

1. Introduction

Polymeric materials have become valued on the market due to their physical and mechanical properties. The main reasons for the increase in the importance of plastics include their low price, resistance to corrosion and chemicals, mechanical strength, impact resistance, ease of forming, and the possibility of recycling way [1].

The possibility of using plastics in many branches of the economy has led to the development of new methods for the measurement of flame retardency. One of the methods used to delay the combustion process is the use of combustion inhibitors. The correct choice of fire-resistance enhancing agent requires considerable knowledge of many fields related to the combustion process, examples include chemical kinetics, heat and mass transport theory, mechanics and fluid dynamics. The selection process is further complicated due to the existence of a large number of materials that differ in construction and composition. Due to the different properties and chemical compositions of different materials, a huge range of flame retardants has been created [2].

Currently, the production of polymers and flame retardants is one of the fastest growing branches of the chemical industry. At present, the global consumption of flame retardants exceeds two million tons per year. It is predicted that in 2018, the global consumption of flame retardants will total almost three million tons. About 85% of flame retardant manufacture is used for the production of plastics, the rest is used in rubber and textile products [3].

Figure 1 shows the actual and predicted applications of flame retardants over ten years from 2014. They are used in plastics, electrical devices, and wires and cables to treat potentially flammable materials. An increasing tendency of applications of flame retardants is observed, mainly due to the development of production of polymeric materials, but also introduced regulations and restrictions on fire protection and environmental protection.

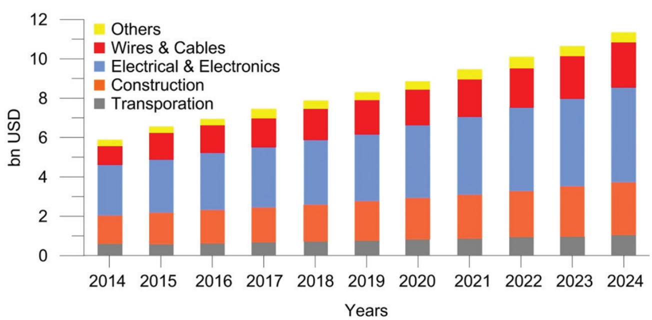

Fig. 1. The global flame retardants market 2014–2024 [4]

2. Flame retardants used for reducing the flammability of materials

Currently, the most frequently applied method of flame retarding polymers and polymeric materials is the use of flame retardants (FR). The growing demand for plastics in many industrial sectors has led to the development of fire retardant production.

Flame retardants are a diverse group of chemicals that are added to materials to reduce their flammability. The right choice of flame retardants is not easy due to the very large amount of different polymeric materials which differ with regard to their construction and composition. When selecting the quantity and type of flame retardant, it is also necessary to take into account the destination of the product, which we want to protect and the degree of fire hazard [5]. However, there are certain requirements that should be met by any well-chosen flame retardant [2]:

a) chemical and physical stability during usage,
b) no degradation of the physical and mechanical properties of the materials,
c) the formation of a homogenous mixture with a polymer matrix,
d) high level of effectiveness with low content in the material,
e) the lowering of the temperature of pyrolysis and changing its course,
f) the lowering of the temperature of the material and catalysing the heat-absorbing reaction,
g) the emission of non-flammable gases that dilute the pyrolysis products and the inhibition of ignition,
h) no emission of toxic substances that are conducive to corrosion processes,
i) resistance to UV radiation and water,
j) affordability and availability on the market,
k) environmentally friendly.

The main purpose of using flame retardants is to interrupt the self-sustaining burning process of the material, which is shown in Fig. 2.

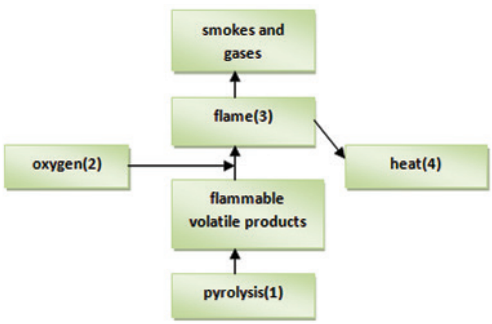

Fig. 2. Diagram of the self-sustaining process of burning material [6]

Stages 1 to 4 represent the points at which the combustion process can be interrupted by the use of flame retardants. Flame retardants can interfere with this process by [6]:

1) changing the course of pyrolysis by creating a charred protective barrier and reducing the amount of flammable, volatile, low molecular weight products;
2) cutting off the oxygen supply;
3) reducing the rate of flame propagation with compounds that deactivate free radicals, e.g. halogen compounds;
4) limiting the amount of heat released to prevent further pyrolysis.

2.1. The mechanism of flame retardant action

Due to the complexity of the combustion process, the mechanism of the action of flame retardants is difficult to determine. Its course is influenced by both chemical and physical reactions. From a chemical point of view, combustion is the reaction of the oxidation of organic compounds accompanied by heat emission. The combustion process starts with ignition, which initiates the energy stimulus. When the temperature is very high, there is also a risk of self-ignition. As the temperature rises, the individual combustion stages follow. The first stage is the elimination of functional groups, halogen atoms or water molecules. The second stage is the cracking of chemical bonds and the formation of small molecule compounds. The third stage is the oxidation of the resulting thermal decomposition products [7, 8]. The combustion process can be occur out according to several mechanisms simultaneously. The effects of the combustion process include the physical and chemical construction of the polymer and the flame retardant, ambient conditions and the presence of other modifiers [2].

2.1.1. The chemical mechanism of flame retardants

The chemical modification consists in the use of reactive flame retardants. These retardants form a coherent whole with the polymer via a covalent bond, making it difficult to isolate them from the polymer matrix. Their addition to the polymer means that they do not move to the surface of the material and do not oxidize during use. Chemical reactions affecting the combustion process may occur either in the gas phase or in a solid phase. The reactions in the gas phase leads to the deactivation of free radicals; this produces more favourable conditions for the occurrence of the combustion process. As a result of the polymer-flame retardant reaction, products are formed that scavenge the radicals from the surface of the polymer or react with them to deactivate them. Decreasing the activity of radicals reduces the flame temperature and the burning rate. There are two categories of solid phase reactions. The first of these concerns the creation of low molecular weight compounds with low melting points, which lower the temperature in the combustion zone and inhibit the propagation of flames. The second category is related to the formation of a porous carbon layer on the surface of the polymer. Reactive flame retardants include organic compounds containing non-flammable elements, for example: polyols, hexabromo phthalate. The reactive fire retardant can also be a functional group, a fragment of the molecule or an element that inhibits the combustion process [2, 8].

2.1.2. The physical mechanism of flame retardants

An alternative solution to reduce the flammability of materials is physical modification; this involves the use of additive (non-reactive) flame retardants. Unreactive fire retardants do not form an integral part of the material, they are introduced into finished products as part of the manufacturing process. They are usually used as mineral fillers, plasticisers, protective coatings, and compounds capable of decarboxylation and dehydration.

The physical mechanism of the action of flame retardants is based on [2]:

a) reducing the degree of polymer degradation;
b) the creation of insulating and barrier layers that block the flow of energy and mass between the solid and gaseous combustion phases;
c) change of the thermal state of the polymeric material with the use of additives of high thermal conductivity and heat absorbing inhibitors;
d) dilution of volatile pyrolysis products with non-flammable gases;
e) extending the duration of pyrolysis.

2.2. Classification flame retardants

Flame retardants can be divided into two basic groups:

a) Flame retardant compounds associated with the polymer during synthesis or crosslinking. These compounds are mainly used to reduce the flammability of epoxides, polyesters and polyurethanes. Examples of such compounds are polyols containing nitrogen, phosphorus and halogens.
b) Non-reactive compounds relative to the polymer added at the time of processing, mainly used in the case of thermoplastics. This group includes halogen compounds, brominated diphenyl oxides, chlorinated and brominated paraffins, hydroxides, bromine and antimony compounds.

Table 1. Classification of flame retardants [2, 5, 9]

Group	Example	Properties
organic halogen compounds	decabromodiphenyl oxide (DECA)	strong resistance to high processing temperature and atmospheric ageing of products; does not affect the colour of materials; is added to the polymer in low concentrations
	dechlorane plus	has a high melting point which does not affect the degradation of the polymer or change its colour; increases the modulus of elasticity and thermal capacity of the polymer without diminishing the insulation properties and resistance to external factors
phosphorus compounds	red phosphorus	reduces smoke emission and corrosion in decomposition products; forms a thermal insulation layer on the surface of the burnt material
	phosphoric acid	is a volatile product of the destruction of phosphorus compounds; forms on the surface of the material; accelerates the carbonation process; eliminates volatile combustible products
	guanylurea phosphate	a compound used to impregnate and reduce the flammability of wood
inorganic hydroxides	aluminium hydroxide	has the form of white powder; forms on the polymer surface as a glass layer that inhibits the spread of flame; reduces the toxicity of fumes; reduces endothermic dehydration
	magnesium hydroxide	white, crystalline powder; shows greater thermal stability than ATH; reduces smoke emission; changes the colour of smoke from dark to light

Table 1 (cont.)

other inorganic compounds	basic aluminium oxalate (BAO)	white powder; reduces flammability and improves the electrical properties of materials
	aluminium salts of phosphoric acid	combustion inhibitors of oxygen-containing polymers in the main chain
	boron compounds	effectively operate in the condensed phase; capable of endothermic reactions leading to the release of water and the formation of a protective vitreous layer; enhance the action of mainly chlorine inhibitors; reduce smoke emission
tin-zinc compounds	zinc hydroxystannate (ZHS)	small size; very low toxicity; flame retardation and smoke formation; the ability to create a surface barrier; blocking the transport of heat from the combustion zone to the deeper layers of the material
	zinc stannate (ZS)	

3. Determination of the flammability of a selected group of polymeric materials

There are many methods for testing the flammability of polymers and polymeric materials. One of the most frequently applied is the oxygen index method. This is a very accurate method, which produces repeatable results for samples that burn completely, even if the tests are conducted in different laboratories. This method can also identify the flammability of materials that do not completely burn, but in this case, the measurement accuracy is lower. The existence of many theoretical correlations between the value of *OI* and other properties determining the flammability of materials makes it possible to determine the combustibility of the material without performing tests [2, 8].

3.1. Combustion reactions of selected polymeric materials

Three theoretical equations have been selected for calculation; these enable determining the value of the oxygen index by knowing other parameters related to the flammability of a given material.

1) Johnson's equation $OI = 7.95 \cdot 10^5 \cdot Q^{-1}$
2) Modified Johnson's equation $OI = 0.0184 \cdot \mathrm{M} \cdot N_x^{-1}$
3) Krevelen's equation $OI = 17.5 + 0.4 \cdot CR$

where:

OI – oxygen index,
Q – heat of combustion,
M – molecular weight of monomer,
N_x – the number of moles of oxygen,
CR – char residue.

Table 2 presents the combustion reactions of selected materials. The total combustion reaction is presented due to the fact that most of the selected materials are burned without leaving a solid residue, which is characteristic of total combustion. In addition, the selected equations give more accurate results if the material burns completely.

Table 2. Combustion reactions of selected polymeric materials

Material	Chemical formula	Combustion reactions
polypropylene	C_3H_6	$C_3H_6 + 4.5O_2 \rightarrow 3CO_2 + 3H_2O$
polyethylene	C_2H_4	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$
polyvinyl chloride	C_2H_3Cl	$C_2H_3Cl + 2.5O_2 \rightarrow 2CO_2 + H_2O + \uparrow HCl$
polystyrene	C_8H_8	$C_8H_8 + 10O_2 \rightarrow 8CO_2 + 4H_2O$
poly(ethylene terephthalate)	$C_{10}H_8O_4$	$C_{10}H_8Cl + 10O_2 \rightarrow 8CO_2 + 4H_2O$

The parameters necessary for calculations are presented in Table 3.

Table 3. Parameters used in calculations [2, 10]

Material	Heat of combustion [MJ/kg]	Molecular weight of mer [g/mol]	Number of moles of oxygen [mol]	Char residue [%]
polypropylene	44	42	4.5	0
polyethylene	44.5	28	3	0
polyvinyl chloride	20	62.5	2.5	15.3
polystyrene	40.5	104	10	0
poly(ethylene terephthalate)	22	192	10	5.1

3.2. Calculated *OI* values for materials based on empirical equations

The table and figure below present the calculation results calculated from individual equations. For each material, the calculated value of the oxygen index was compared to the experimental value with and without the addition of flame retardant.

The materials were classified according to the flammability criterion characteristic of the oxygen index method [2] :

- *OI* ≤ 21% – flammable,
- *OI* > 21% – retardant,
- *OI > 60%* – non-flammable.

The calculations show that for compounds which burn completely without leaving any solid residue, the equations above are better suited than materials that do not completely burn. These compounds are polypropylene, polyethylene and polystyrene. In the case of these materials, slight differences between the value of the oxygen index determined experimentally and calculated from theoretical equations can be observed; the errors are on average: 0.47% (PP), 0.49% (PE), 1.26% (PS). Johnson's equation works best for polyethylene and polypropylene with regard to the heat of combustion. In the case of polystyrene, the highest consistency of results is obtained using van Krevelen's equation, which takes into account the amount of solid residue after combustion.

Table 4. Calculated *OI* values for materials based on empirical equations [2, 8, 11, 12]

Material	Experimental *OI*		Theoretical *OI*			Classification
	without FR	with FR	Johnson's equation	Modified Johnson's equation	Krevelen's equation	
PP	0.185	0.240	0.181	0.172	0.175	flammable
PE	0.180	0.230	0.179	0.172	0.175	flammable
PVC	0.220	0.280	0.398	0.460	0.236	flammable
PS	0.175	0.240	0.196	0.191	0.175	flammable
PET	0.210	0.235	0.361	0.353	0.195	flammable

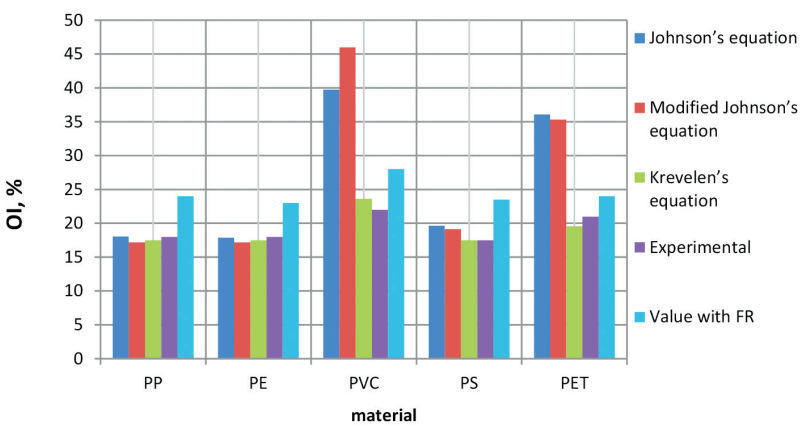

Fig. 3. Oxygen index values for a selected group of polymeric materials

Compounds that are not completely burned, give worse equals in the applied theoretical equations. Only in the case of poly (ethylene terephthalate) and polyvinylchloride, does no combustion occur. These polymers leave a char residue. The resulting coke layer protects the material, limiting the access of oxygen and thus inhibits the progress of destruction. This involves more O_2 being needed to initiate the combustion reaction.

Upon analysing these materials, larger discrepancies were found between the theoretical value and the laboratory value. The average error value for PVC is 14.5%, and for PET it is 10.3%. Both polyvinyl chloride as and poly (ethylene terephthalate) used in solve the Johnson equation, give to the worst results. The explanation for this may be the low value of the heat of combustion. It can be observed that the value of the heat of combustion in their case is twice as low compared to the heating value of PP, PE and PS. An additional effect on the deterioration of the applicability of these equations is the presence of the chlorine atom in the PVC molecule. Johnson equations, taking into account both the heat of combustion and the molecular weight of the mer and the moles of oxygen, provide exact results only if the material contains carbon, hydrogen and oxygen in its composition.

4. Summary

- The possibility of using polymeric materials in many industrial sectors has influenced the development of new methods for reducing and testing flammability.
- The reason for the increase in the production of flame retardants is not only the ever-growing demand for polymeric materials but also the regulations and restrictions on fire protection and environmental protection.
- Until present, no flame retardant has been found that meets all the characteristics of a good combustion inhibitor.
- The applied Johnson and Krevelen models only partly take into account the structure of the material, the composition and shape of the polymer as well as the conditions of combustion of the sample. The value of the oxygen index determined theoretically should be treated as an approximate value.
- By comparing the value of the oxygen index for individual materials both with and without the addition of FR, one can assess the effectiveness of their operation. It is observed that after the addition of flame retardants, there is an increase in the *OI* value and thus, the flammable properties of the analysed materials are improved. The size of the growth of the *OI* value is undoubtedly influenced by the type of flame retardant used and also by the type of material.
- Compounds that burn completely meet the requirements of the Johnson (PE, PP) and the Krevelen (PS) equations ($\delta OI \sim 0.7\%$). The calculated oxygen index for PVC and PET materials after combustion (which leaves coke breeze) significantly differs from the experimental value ($\delta OI \sim 12.4\%$).
- The increase in the OI value is influenced by the type of flame retardant used and type of material.

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Parameters of the Carslaw-Jaeger equation describing the temperature distribution in the ground

Parametry równania Carslawa-Jaegera opisującego rozkład temperatury w gruncie

Abstract

The ground temperature changes with depth and time. Time variability is considered as a harmonic function. The equation describing changes of the ground temperature contains four parameters: the average annual temperature of the surface of the ground, the annual amplitude of the temperature of the ground surface as well as the phase angle of the temperature and thermal diffusivity of the ground. Based on the results of the measurements presented in the literature, the parameters of the equation using the combined method on the basis of linear regression, described in the literature, were determined. This method, however, leads to an ambiguous value of the thermal diffusivity. It was found that the nonlinear regression method gives much better results, leading to obtaining precise and unambiguous values of all parameters of the equation.

Keywords: temperature distribution in the ground, nonlinear regression

Streszczenie

Temperatura gruntu zmienia się z głębokością oraz w czasie. Zmienność czasowa ma charakter harmoniczny. Równanie opisujące zmiany temperatury gruntu zawiera cztery parametry: średnioroczną temperaturę powierzchni gruntu, roczną amplitudę temperatury powierzchni gruntu, kąt fazowy oraz dyfuzyjność cieplną gruntu. Na podstawie wyników pomiarów przedstawionych w literaturze wyznaczono parametry równania kombinowaną metodą opierającą się na regresji liniowej, opisaną w literaturze. Metoda ta prowadzi jednak do otrzymania niejednoznacznej wartości współczynnika dyfuzyjności cieplnej. Stwierdzono, że znacznie lepsze wyniki daje metoda regresji nieliniowej, prowadząc do otrzymania dokładnych i jednoznacznych wartości wszystkich parametrów równania.

Słowa kluczowe: rozkład temperatury w gruncie, regresja nieliniowa

1. Introduction

Knowledge of the temperature distribution in subsurface ground layers is important in the design, modelling and exploitation of ground heat exchangers and other devices related to heat transport in the ground (for example, pipes transporting heat carriers). The ground can be treated as a system composed of a subsurface layer in which there are interactions related to changing weather conditions as well as a deeper layer in which these impacts do not occur.

The ground temperature depends on the latitude, weather conditions, season, altitude, topography, shading, presence of buildings in the neighbourhood, type of surface coverage, ground properties and precipitation. Because many of these parameters change in the seasonal cycle, or irregularly with time, it is not possible to accurately predict the temperature of the ground at any location and at any time, especially in places close to the ground surface. Therefore, the prediction of ground temperature has a statistical nature.

The ground temperature in the subsurface layer depends on the location and time. The thickness of this layer depends on the thermal diffusivity of the ground. For small values of thermal diffusivity, the subsurface layer has a small thickness, whereas when the thermal diffusivity of the ground is high, the ground temperature stabilisation at the level of the undisturbed ground temperature, occurs at greater depths [1]. Due to the thermal inertia of the ground, the amplitude of the ground temperature changes decreases with depth. The amplitude of ground temperature changes caused by daily variability of the ground surface temperature decreases to zero at a depth of about 1 m, while the amplitude caused by seasonal changes decreases with the distance from the ground surface to a much lesser degree.

Carslaw and Jaeger [2] presented a relationship describing the ground temperature as a function of the location (distance from the surface) and time. It is a solution to the equation of heat conduction for the semi-infinite body with a periodic temperature change of its surface.

The results of extensive studies of temporal changes of the ground temperature at various depths in various climatic conditions in the USA were presented by Kusuda and Achenbach [3]. Some of the results of these experiments form the basis for the analysis carried out in the remainder of this paper.

Ground temperature measurements at various depths and in various places around the world are often published in the literature. For example, Badache et al. [4] presented the results of research carried out in Montreal; the ground was analysed to a depth of 26 m. However, the results of research carried out in Poznan City, presented by Popiel and Wojtkowiak [5], concerned research in the depth range up to 17.3 m.

Based on the analysis of the heat fluxes occurring on the ground surface, the surface temperature of the ground can be related to the air temperature, which is characterised by the following parameters: average annual value, annual fluctuation amplitude and phase angle [6, 7].

In this paper, the parameters of the Carslaw-Jaeger equation were determined based on the results of ground temperature measurements at various depths. The method used by Kusuda and Achenbach [3] and nonlinear regression were applied. The benefits of nonlinear regression have been presented. Differences between average annual temperature, annual temperature amplitude and phase angle for the ground surface and for the air were also discussed.

2. The Carslaw-Jaeger equation

For theoretical analysis of ground temperature changes with location and time, the following assumptions are made:

- The ground is a homogeneous heat conducting medium,
- The ground can be treated as a semi-infinite medium with constant thermal diffusivity,
- The surface temperature of the ground is variable periodically over time.

The problem of ground temperature has been examined for a long time. The first known works of Lord Kelvin come from 1811. The ground temperature can be described using the Fourier series:

$$T = T_{sm} + \sum_{n=1}^{\infty} A_{sn} \cdot \exp\left(-\sqrt{n}\frac{x}{L}\right) \cdot \cos\left(n\omega t - P_{sn} - \sqrt{n}\frac{x}{L}\right) \tag{1}$$

where:

x – position coordinate [m],
t – time [s],
T_{sm} – annual average temperature of the ground surface [°C],
L – damping depth [m].

The A_{sn} [K] and P_{sn} [rad] values correspond respectively to the n^{th} harmonic component: the annual amplitude of temperature fluctuations on the ground surface and the phase angle. Often, the above relationship is simplified to the form in which only the first expression of the series occurs. This is justified because the higher harmonic elements generally relate to the daily temperature variations of the ground, which is not taken into account here. For $n = 1$ the equation has the form:

$$T = T_{sm} - A_s \cdot \exp\left(-\frac{x}{L}\right) \cdot \cos\left(\omega t - P_s - \frac{x}{L}\right) \tag{2}$$

Carslaw and Jaeger [2] in the monograph *Conduction of Heat in Solids* presented the above dependence as a solution to the equation of heat conduction in a semi-infinite medium whose surface has a periodically variable temperature (this equation was presented by Carslaw in the first edition of the work [8] already in 1906). The solution is of practical importance in determining the temperature of the ground subjected to cyclical actions related to seasonal changes. The solution concerns the case when the geothermal gradient is zero. The damping depth L is defined as follows:

$$L = \sqrt{\frac{2a}{\omega}} \tag{3}$$

where:

a – thermal diffusivity of the ground [m^2/s],
ω – frequency of temperature changes [$days^{-1}$] or [s^{-1}].

Phase angle P_s is related to the time $t_{\min}$ elapsing from the beginning of the calendar year to the day on which the average daily temperature of the ground surface reaches the minimum value:

$$P_s = \omega t_{\min} \tag{4}$$

For the phenomena occurring in the annual cycle, the frequency is $\omega = 2\pi/365$ days^{-1}. Due to the neglect of the geothermal flux, the value of the average annual ground temperature T_m practically does not depend on the location. Consequently, the undisturbed ground temperature and the annual average surface temperature of the ground are equal.

By introducing substitutions:

$$T_m = T_{sm} \tag{5}$$

$$A_x = A_s \cdot \exp\left(-\frac{x}{L}\right) \tag{6}$$

$$B_x = P_s + \frac{x}{L} \tag{7}$$

the following dependency is obtained:

$$T = T_m - A_x \cdot \cos\left(\omega t - B_x\right) \tag{8}$$

from which it is possible to specify the values of T_m, A_x and B_x for individual depths x.

It should be noticed that in some situations the equation (2) must be modified to reflect the real temperature distribution in the ground [9]. This concerns i.a. the case where, due to the presence of groundwater, there is, besides conduction, additional convective heat transfer in the ground. Furthermore, in a cold climate due to the freezing of the ground and snow cover, the relationship (2) does not properly describe the temperature distribution in the ground.

3. Determining the parameters of the Carslaw-Jaeger equation

The parameters of Carslaw and Jaeger equation are: average annual temperature of the ground surface T_{sm}, annual amplitude of temperature fluctuations of the ground surface A_s, phase angle P_s and damping depth L.

Kusuda and Achenbach [3] used the model (2) to determine the parameters T_{sm}, A_s, P_s and L. The method of calculating these parameters based on the results of the measurements presented in Fig. 1 is presented below. The measurements concerned monthly average ground temperatures, averaged over many years, carried out in Argonne (Illinois, USA). Measurements were taken at depths from 0 to 8.84 m, and the results covered all months of the year. Fig. 1 shows exemplary results for four selected months.

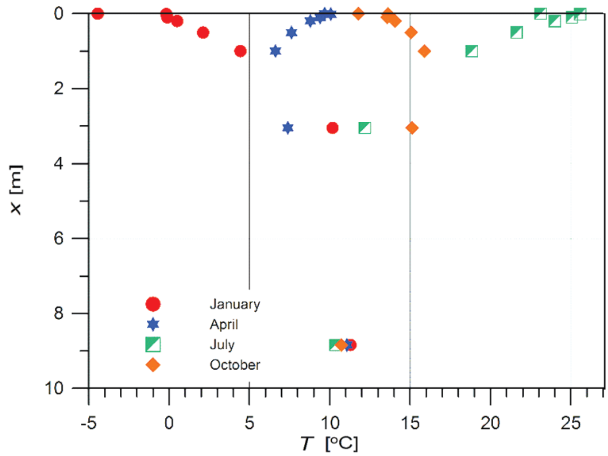

Fig. 1. Sample results of measurements of monthly average ground temperatures at various depths [3]

For the calculations, 96 (= 12·8) values of soil temperature measurement data were used. The indirect results of the calculations are presented in Table 1. The following values are given: the position coordinate x and the coefficients b_0, b_1 and b_2 of the equation (A.2) (presented in Appendix A) in a linearised form of dependence (8). The relationship between T_m and x, as shown in Fig. 2, suggests averaging the values T_m, which gives the value T_{sm} = 11.1°C.

Table 1. The results of the calculated parameters of equations (A.2) and (8)

x [m]	$b_0 = T_m$ [°C]	b_1	b_2	B_x [rad]	A_x [K]
0	9.47	–11.29	–7.853	0.608	13.75
0.01	11.78	–10.45	–8.027	0.655	13.18
0.10	11.46	–10.17	–8.125	0.674	13.02
0.20	11.36	–9.18	–8.209	0.730	12.31
0.50	11.29	–6.90	–8.082	0.864	10.62
1.00	11.33	–4.06	–7.516	1.075	8.54
3.05	11.26	1.10	–3.770	–1.288+π	3.93
8.84	10.89	0.29	0.397	0.942+π	0.49
Average value	T_{sm} = 11.10				

The consecutive values in the table are B_x and A_x, determined according to the dependencies (A.8) and (A.9) presented in the Appendix. In Fig. 2, the relation between A_x and x is shown in a semi-logarithmic system. Since the relationship is approximately linear, the approximation with equation (6) can be used. In this way, the following parameters were determined: A_s = 13.1 K and L = 2.67 m. The same figure also shows the dependence of B_x on x. The points are arranged on a straight line, which is consistent with the formula (7). The determined constants are: P_s = 0.651 rad and L = 2.57 m. Thus, the values of parameters L, A_s and P_s were determined, with the damping depth determined by two methods: amplitude and phase angle, yielding different results.

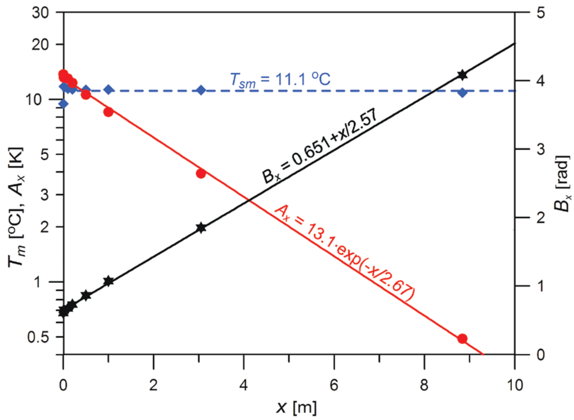

Fig. 2. Dependence of T_m, A_x and B_x on the position coordinate x

Another way to determine the parameters of equation (2) is the use of nonlinear regression. An iterative method was applied consisting in the repeated use of the least squares technique for different values of damping depth L. The calculation method for the known L value is shown in Appendix B. The estimated value of parameter L corresponds to the minimum sum of squared errors of experimental and calculated SS values.

The parameters of equation (2) can also be determined by nonlinear regression directly e.g. by using the Solver application from the Excel package. The minimum value of SS is sought, with the algorithm based on solving the algebraic system of nonlinear equations. As initial values the following parameters L = 2 m, T_m = 10°C, A_s = 12 K and P_s = 0.5 rad were assumed. Then the ground temperature was calculated using Eq. (2). Parameters presented in Table 2 (Excel) were obtained for the minimum sum of squared errors is SS = 73.48.

Table 2. alculation results of the equation (2)

	Amplitude method [3]	**Phase lag method [3]**	**Nonlinear regression (App. B)**	**Nonlinear regression (Excel)**	**Designated in [3]**
Average temperature T_m [°C]	11.1	11.1	11.1	11.1	10.6
Amplitude A_s [K]	13.1	13.1	13.4	13.4	12.8
Phase angle P_s [rad]	0.651	0.651	0.639	0.634	0.7
Damping depth L [m]	2.67	2.57	2.38	2.38	2.60

Table 2 presents the values of the parameters of equation (2) obtained:

- Application of the equation (8) with the determination of the value L on the basis of the dependence of the amplitude A_x on the x (amplitude method),
- Application of the equation (8) with the determination of the value L based on the dependence of the phase angle on the x (phase angle method),
- By using nonlinear regression with the iterative determination of L value,
- By using the Solver application from the Excel package,
- Designated in the paper [3].

4. The accuracy analysis of the obtained parameters

On the basis of the designated parameter values: T_{sm}, A_s, P_s and L, according to the dependence (2), the soil temperature at different depths and at different periods of the year was determined. The results of the calculations together with the results of the measurements are shown in Fig. 3a, b, c and d. Compatibility with the results of the experiments is good; the best is for parameter values determined from nonlinear regression. Parameter values obtained by nonlinear regression methods: iterative and using the Excel package were identical.

Fig. 4 presents a comparison of experimental and calculation results for the entire time interval and for two coordinate positions: $x = 0.2$ m and $x = 3.05$ m.

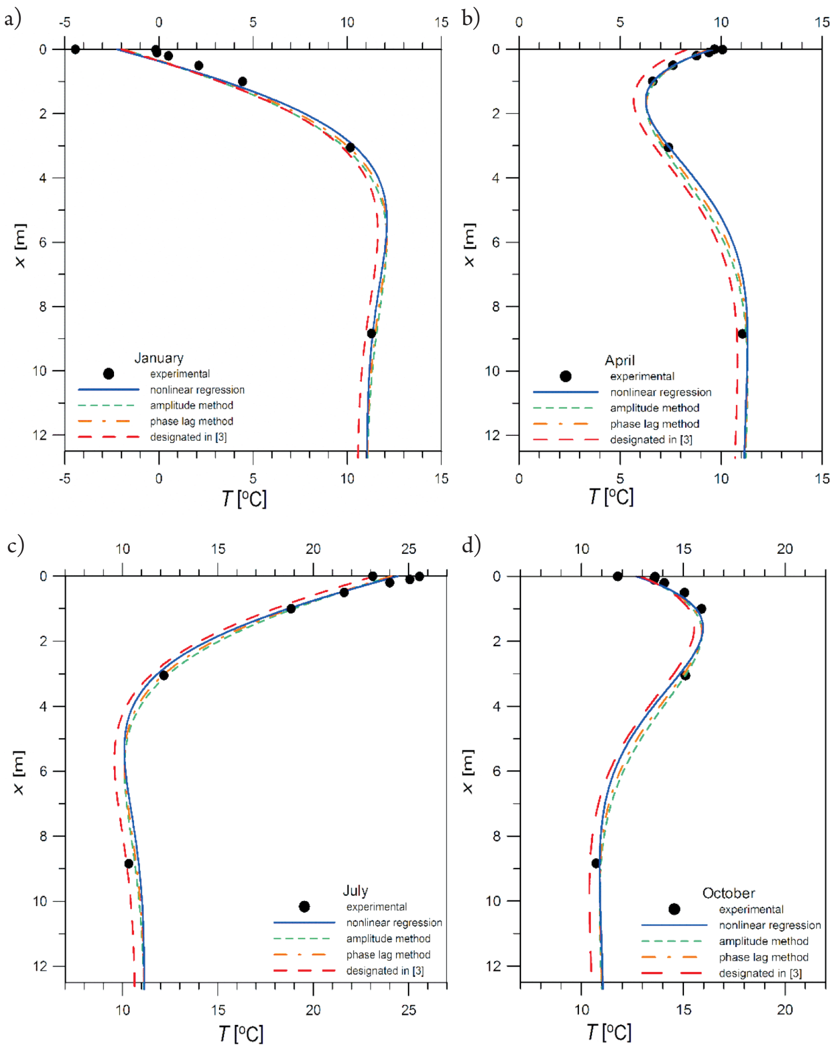

Fig. 3. Comparison of measurement results with the results of calculations in various methods: a) January, b) April, c) July, d) October

Fig. 3a, b, c, d and Fig. 4 show that the best compliance with the results of the experiment is obtained by nonlinear regression, and the largest deviations refer to computational values determined on the basis of the values given in work [3].

Direct comparison of experimental and computational results obtained by using nonlinear regression and obtained on the basis of values presented in work [3] is shown in Fig. 4. Most absolute errors are smaller than 1.5 K and the biggest errors concern small and large temperature values (occurring at the ground surface). In the middle temperature range, corresponding to the large depths, the errors are low. Moreover, the graph confirms good compatibility between the nonlinear regression calculation results and measurement values.

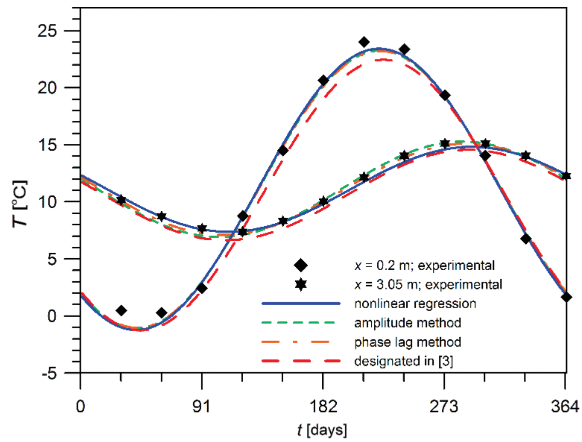

Fig. 4. Comparison of experimental and calculation results for $x = 0.2$ m and $x = 3.05$ m

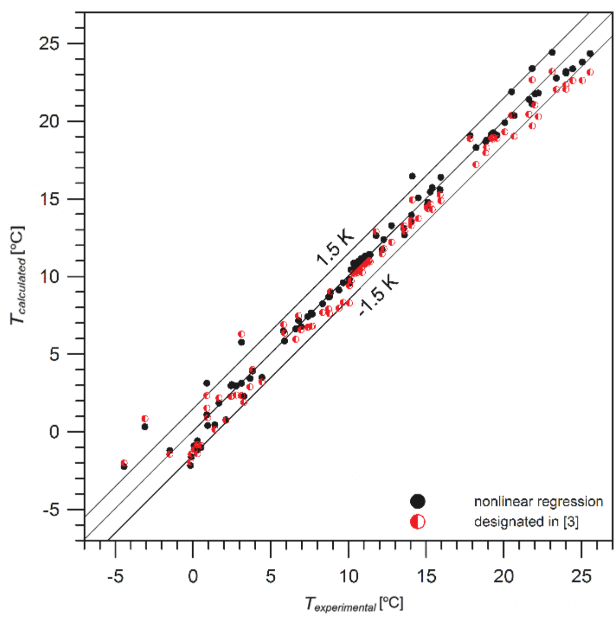

Fig. 5. Compatibility of experimental and calculation results

The average deviation between experimental and computational temperatures (based on the values of parameters determined by non-linear regression) is equal to:

$$\sigma = \sqrt{\frac{SS}{n-m}} = \sqrt{\frac{73.48}{96-4}} = 0.89\ \mathrm{K} \tag{9}$$

where:

- n – the number of measurements,
- m – the number of determined parameters.

5. Comparison of the values of the equation parameters determining the ground surface and the ambient temperature

It is interesting to compare the values of the parameters of equation (2): T_{sm}, A_s and P_s with the values of the parameters of the equation describing the temporal variability of the ambient temperature:

$$T_a = T_{am} - A_a \cdot \cos\left(\omega t - P_a\right) \tag{10}$$

In the above equation: T_{am} – average annual ambient temperature [°C], A_a – annual amplitude of ambient temperature fluctuations [K], P_a – phase angle for ambient temperature corresponding to the time which elapses from the beginning of the calendar year to the day in which the average ambient temperature reaches the minimum value [rad]. In work [3], the appropriate values were compared, and it was found that:

- For many sites, near equality of the average annual ambient temperatures T_{am} and the average annual temperature of the ground T_{sm} can be approximated. This regularity does not apply to mountain climates.
- For inland sites, the amplitude of the ground surface A_s is less than the amplitude of the ambient temperature A_a. The reverse relation concerns areas near the coast.
- The phase angles of the annual ambient temperature cycles are concentrated in a narrow range (deviations ±0.05 radians), while the phase angles of the temperature of the ground surface are dispersed in a wider range (deviations ±0.2 radians).

6. Conclusions and final remarks

In this paper, the parameters of the Carslaw-Jaeger equation were determined based on the results of ground temperature measurements at various depths. A combined method based on the linear regression and the nonlinear regression method was used. It was found that the first method leads to ambiguous values of the thermal diffusivity. The nonlinear regression method gives much better results, leading to precise and unambiguous values of all parameters of the equation.

Compatibility of computational values with the results of experiments is good; the best for values of parameters determined from nonlinear regression. Most of the absolute errors are less than 1.5 K. The biggest errors concern temperatures measured near the ground surface.

As the data for the calculations, the measurement values presented in work [3] were used, which refer to monthly average temperature values. Temperature values had to be assigned to the time values. When assigning temperature values for the k^{th} month to the time values (k-0.5)·365/12 (day of the year corresponding to the middle of this month), the obtained phase angle values P_s were less by about 0.26 rad than the value given by the authors. Since this difference corresponds to $t \approx 15$ days, further calculations were carried out by assigning temperature in the k-th month time k·365/12, which corresponds to the end of the month (Fig. 4). Therefore, the P_s value should be considered as contractual, depending on the assumed origin of the time-coordinate system.

Appendix A. Linear regression

Using the trigonometric identity:

$$\cos(\alpha \pm \beta) = \cos\alpha \cdot \cos\beta \mp \sin\alpha \cdot \sin\beta \tag{A.1}$$

dependence (8) can be transformed into the form:

$$Y = b_0 + b_1 X_1 + b_2 X_2 \tag{A.2}$$

where the dependent variable $Y = T$ and the independent variables are defined as follows:

$$X_1 = \cos(\omega t) \tag{A.3}$$

$$X_2 = \sin(\omega t) \tag{A.4}$$

The coefficients from the equation (A.2) are associated with the coefficients from the equation (8):

$$b_0 = T_m \tag{A.5}$$

$$b_1 = -A_x \cdot \cos B_x \tag{A.6}$$

$$b_2 = -A_x \cdot \sin B_x \tag{A.7}$$

After determining the coefficients b_0, b_1 and b_2 using the least squares method, B_x and A_x can be calculated according to the formulas resulting from (A.6) and (A.7):

$$B_x = \arctan\left(\frac{b_2}{b_1}\right) \tag{A.8}$$

$$A_x = -\frac{b_2}{\sin B_x} \tag{A.9}$$

Appendix B. Nonlinear regression

It is not possible to transform the equation (2) to the linear form due to the determined parameters T_{sm}, A_s, P_s and L. However, the problem can be solved by using an iterative method relative to the parameter L. The used algorithm consisted in a trial assumption of L and calculation of the sum of squared errors SS. By reiterating that calculation, the L value, for which the SS value reaches the minimum, can be determined.

For the trial value L, the equation (2) can be reduced to the form:

$$Y = b_0 + b_1 X_1 + b_2 X_2 \tag{B.1}$$

where the dependent variable $Y = T$ and the independent variables are defined as follows:

$$X_1 = \exp\left(-\frac{x}{L}\right) \cdot \left[\cos\left(\frac{x}{L}\right) \cdot \cos(\omega t) + \sin\left(\frac{x}{L}\right) \cdot \sin(\omega t)\right] \tag{B.2}$$

$$X_2 = \exp\left(-\frac{x}{L}\right) \cdot \left[\cos\left(\frac{x}{L}\right) \cdot \sin(\omega t) - \sin\left(\frac{x}{L}\right) \cdot \cos(\omega t)\right] \tag{B.3}$$

wherein the trigonometric identity (A.1) was used.

The coefficients from equation (B.1) are associated with the coefficients from equation (2):

$$b_0 = T_m \tag{B.4}$$

$$b_1 = -A_s \cos(P_s) \tag{B.5}$$

$$b_2 = -A_s \sin(P_s) \tag{B.6}$$

After determining the coefficients b_0, b_1 and b_2 using the least squares method, P_s and A_s can be calculated according to the formulas resulting from (B.5) and (B.6):

$$P_s = \arctan\left(\frac{b_2}{b_1}\right) \tag{B.7}$$

$$A_s = -\frac{b_2}{\sin(P_s)} \tag{B.8}$$

The last step of the algorithm is to calculate, according to (2), the value of temperature $T_{calculated}$ based on the sample values of parameters T_m, A_s, P_s and L, and then the calculation of the sum of squared errors of calculation and experimental values according to the formula:

$$SS = \sum_{i=1}^{n} \left(T_{calculated} - T_{experimental}\right)^2 \tag{B.9}$$

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Determinants of land developers' activity in Poland

Determinanty działalności land deweloperskiej w Polsce

Abstract

The proper use of space, particularly in urban areas, has become very important. Land developers are focused on activities which increase the value of land by preparing it for investment (the purchase of land, transforming it into the building area, merging or division of land into smaller parcels, utilities, and the final sale to other developers). In this article, land development activity is also considered as part of the development process. The aim of this study is to identify the factors that determine the manner of activities related to the procurement and preparation of land for construction by developers. The research is an important step towards the creation of the concept of land developers' activity in Poland.

Keywords: land developer, development project, land use, land development

Streszczenie

Obserwując zmiany zachodzące w zagospodarowaniu terenów w Polsce, można stwierdzić, że duży udział tych przemian wynika z działalności deweloperskiej. W długim okresie działania deweloperów wymuszają istotne przeobrażenia gruntów. Z kolei grunty jako kapitał stanowią zasadniczy element gospodarki rynkowej I, co najważniejsze, są zasobem ograniczonym. W Polsce aktywność deweloperów obserwowana jest głównie na rynku nieruchomości mieszkaniowych. To powoduje, że często przez pryzmat tej działalności definiuje się dewelopera, traktując go jako przedsiębiorstwo budujące mieszkania na sprzedaż. Rozwinięte rynki nieruchomości wyróżniają deweloperów działających zarówno w segmencie nieruchomości mieszkaniowych, jak i komercyjnych (biurowe, handlowe, magazynowe itp.), ale także zajmujących się tylko przygotowaniem gruntów pod przyszłą zabudowę. W Polsce dotychczasowe czynniki rynkowe nie wymusiły aż tak daleko idącej specjalizacji działalności deweloperskiej. Dlatego wachlarz usług świadczonych przez deweloperów jest dość szeroki. Celem artykułu jest identyfikacja czynników mających wpływ na przeobrażanie i przygotowanie gruntów przez deweloperów. Przeprowadzone badania są częścią tworzenia koncepcji działalności land deweloperskiej.

Słowa kluczowe: land deweloper, projekt deweloperski, zagospodarowanie terenu, planowanie przestrzenne

1. Introduction

Analysing the changes in land use in Poland, it can be observed that a large share of these changes results from developers' activity. In addition, land as capital is an essential part of the market economy and most importantly, it is a limited resource. Therefore, the proper use of space, particularly in urban areas, is becoming important. Land developers are focused on activities which increase the value of the land by preparing it for investment (the purchase of land, transforming it for building, merging or division of land into smaller parcels and utilities, and the final sale to other developers). In a development project, land is the key factor of production. Issues relating to its identification, selection and development are fundamental during the pre-investment phase. Changes in the property market force developers to professionalise their operations by, among other strategies, making rational use of land resources. The aim of this study is to identify the factors that determine the manner of activities related to the procurement and preparation of land for construction by developers.

2. Literature review

Property development is an extremely complex activity that involves significant numbers of people and skills, using extensive resources over an extended period for the provision of physical buildings in the future. It all starts with the provision of development land. Many studies relevant to developers' activities of land conversion apply to property using opportunities (e.g. real option in American literature) are increasingly being promoted in the academic world for use by developers to make more informed decisions on the timing of property development and the valuation of development land [14]. A real option is valuable in an uncertain economic environment because foregoing development today preserves the opportunity to develop at a later date when additional information is available. Option pricing models built around the basic concept have been used in literature on property development to evaluate: the conversion of land on the urban fringe [1]; time lags between production decisions and the delivery of news pace to the market [13]; flexibility in the timing and intensity of development [20, 3]; information asymmetries [10, 4]. Thus it is worthy of attention in spite of the world of uncertainty and imperfect information. Previous studies mainly based on the financial side of the decisions by developers. In contrast, there are few studies in the literature concerning land conversion issues in the context of the decisions made by developers or land developers. In particular, it seems an interesting area of research in Poland because in recent years, planning laws have allowed developers a reasonable amount of freedom with regard to shaping land use [16].

The importance of the developer in land development models has been extensively analysed my many researchers in previous studies. One of these is the model devised by Drewett [6] who argued that in understanding the land development process, attention should be placed on the developers because they are central to the development process. Drewett shares the idea with some earlier analysts such as Craven [8] and Kaisser and Weiss [11] who argued that the developer is the key coordinator and catalyst for development, whose actions are triggered by perceptions of potential yields. McNamara [16] attempted to incorporate the time factor into a general description of the development process. He further developed this idea into a classifications of developers' interests according to the timescale of their involvement in a development project. An alternative approach was taken by Goodchild and Munton [9] who devised a general model of the land development process based upon two key decision points: the identification of land as being suitable for development; the initiation of construction work upon that land.

3. Metodology

This article is a part of research which was conducted to develop a wider project [12] at the same title. The theoretical part of the elaboration allows identification of the determinants which have an influence on land developers' activity through the application of a survey questionnaire. The survey was conducted among developers who were members of the Polish Union of Real Estate Development Companies. The survey method was aimed at determining the impact of individual factors on land developers' activity in Poland. Here, a *Likert* scale [15] was applied, where five possible answers were specified, ranging from 'no influence' to 'very big influence' The respondents could express the importance of a selected factor by choosing one of the following answers: 1 – no influence, 2 – slight influence, 3 – average influence, 4 – big influence , 5 – very big influence.

4. The essence of land developers' activity

In Poland, developers' activity is mainly observed in the housing market. This means that a developer is often defined as a company that is building apartments for sale. Developed property markets distinguish between developers working in both the residential and commercial sector (office, retail, warehouse, etc.) and land developers. In Poland, the current market factors have not applied such clear-cut distinctions so in this article, land development activity is also considered as a part of the development process. In literature, the term 'land developers' activity' is referred to as development activity leading to transformation of land including: acquiring the land; increasing its value though land conversion; consolidation and division; preparation for a construction project; development of amenities; selling the plots of land at a profit [5, 18].

Such an approach to land developers' activity applies to the conversion of land from agricultural to residential use. In the author's opinion, this is one of the possibilities for running a land development project and it is assumed that land developers' activity is a special form of investment activity which is focused on the development/conversion of land which could be targeted for construction in the future. This approach considers the possibility of conducting land developers' activity not only with agricultural land but also with brownfields, devastated and degraded land or land that is treated as wasteland. This argument seems to be particularly important for reducing urban sprawl and for the implementation of investment projects according to sustainable development rules.

5. Factors influencing land development activity

The determinants of land developers' activity are considered as factors that make up the external environment in which developers carry out activities related to the preparation of land for construction projects. They also include internal factors influencing developers' decisions and kind of activities carried out on land. The external determinants are understood as the environment in which a developer/land developer operates. Internal factors are divided into two groups – those which depend upon conditions relating to the given company and those which depend on the characteristics of potential land for investment and there is indicative of criteria for the decision to purchase and to prepare it for construction. A graphical portrayal of the proposed scheme is shown in Fig. 1.

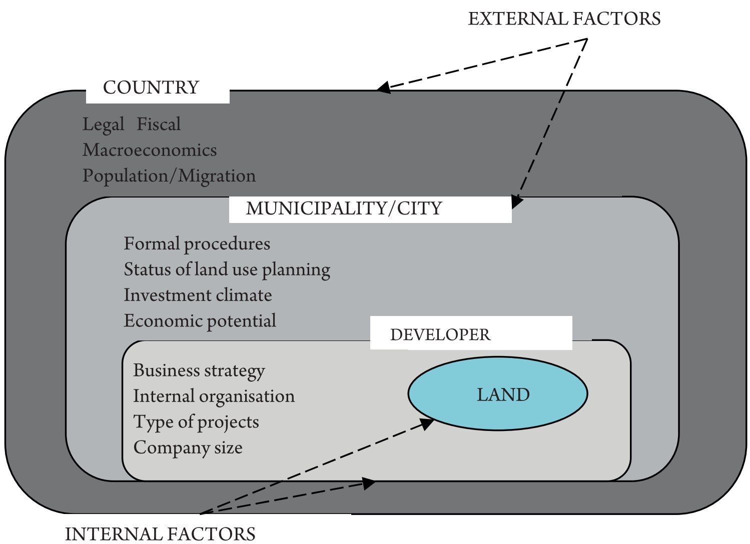

Fig. 1. Determinants of land developers' activity in Poland – conception (source: own study based on the research [12])

The external environment creates certain conditions, the form and influence of which on business is independent and companies often have to submit to them in their activities. The external factors were divided into two groups. In the first group are the conditions observed at country level, such as the legal, fiscal, macroeconomic, demographic determinants. The second group includes factors at the municipality/local level and these are the legal procedures imposed by officials, the planning system, the investment climate and the economic potential.

The group of determinants influencing the land business at country level includes:

- legal conditions of the investment process,
- economic situation in the property market,
- fiscal conditions,
- transaction costs,
- macroeconomics,
- external financing conditions.

The determinants influencing land developers' activity at a local level include:

- land use planning system,
- implementation of the procedures by officials,
- planning fee,
- investment climate,
- economic potential of the area,
- land supply,
- local community,
- ownership.

The list of selected factors was supplemented by two more:

- migration,
- competition among developers

In the author's opinion, these factors can be analysed at the national or municipality level. This depends on whether the development company is running on the local or the national property market.

In order to determine the influence of factors on searching, acquiring and preparing the land for construction, internal factors (depended on the company) were selected. The following factors were included:

- business strategy including creation of land bank, type of development project,
- type of action for preparing land,
- business organisation including number of employees, having expansion division, the way of cooperation with company preparing land,
- legal form (e.g. limited liability company etc.),
- company experience.

Due to specific and individual nature of land, it was necessary to create a second group of internal factors to define the physical characteristics of the land to be developed. These factors are as follows:

- size,
- amenities,
- shape,
- access to public road,
- buildings to be demolished,
- neighbourhood/surrounding area,
- soil contamination and remediation.

Economic and legal conditions are:
- legal status,
- location,
- type of construction,
- potential allocation in land use plan or planning permission.

Internal factors include the following actions which focus on the preparation of land for building projects:
- consolidation and division,
- obtaining the zoning decision.

6. Results of empirical research

The respondents' answers show that all analysed conditions have an impact on the activities that land developers conduct. The average response for all determinants is 3.47 and this means that there is more than a moderate impact of external determinants on the process related to the final preparation of land for building investment projects.

Analysis of the impact of individual determinants was performed according to the aforementioned classification. Among the characteristics observed from the national perspective, the legal conditions of the investment process had the highest rate (4.41). It is worth adding that over 55% of respondents rated the influence as very big, and over 33% rated it as big.

The economic situation on the property market was rated as 3.96 and this was the second highest rating. Almost 30% of respondents recognised it as being very important. Just over 40% of respondents indicated that the significance of this determinant in influencing land developers' activity is big.

The lowest rating (2.92) related to the influence of fiscal conditions which may suggest that tax laws have the least influence on land developers' activity of all factors at the national level. In spite of this, it should be stressed that the score for this factor was close to 3 and this confirms the strength of influence, which is almost average.

The second group of external determinants which concern municipality level received an average of 3.4 points and this means that their influence was more than mid – score. Among the listed factors, the planning state can be said to have the largest influence with an average rating of 4.41. Nearly 70% of respondents concluded that this factor has a very large influence and more than 25% said it had a big influence. The second highest rating was for the factor named as implementation of the procedures by officials with an average 4.25. Of the respondents, 53% assessed its influence as being very big and 30% assessed it as being big.

While assessing both of the abovementioned factors, the lowest value of the answers from respondents was 2, which indicates that all respondents agreed that these factors influence land developers' activities but with different intensities.

The next factor whose influence was assessed as big was the economic potential of area because the average rating was 3.77. Nearly 15% of respondents said that the impact of this factor was very big, almost 50% of them concluded that it was big and about 35% stated that it was average. The lowest rating was 3 in this case.

The average rating of the remaining factors, which ranged from 3.0 to 3.7, were ownership (3.66), land supply (3.48), and investment climate in municipality/city (3.33).

In respondents' ratings, the lowest impact was attributed to factors like local community (2.92) and planning fee (2.4). For more than 60% of respondents, the factor which was defined as local community had a significant importance in activities related to land preparation for building investment; the rest of those questioned assessed its influence as less significant.

In the case of planning fee, 18% of respondents said that this factor had no influence and almost 40% concluded that the impact was low; thus, this last factor was said to be the least significant external determinant.

The last two indicators of external determinants received the following ratings: competition among developers – 3.4, migration – 2.77.

A graphical portrayal of responses is presented in Fig. 2.

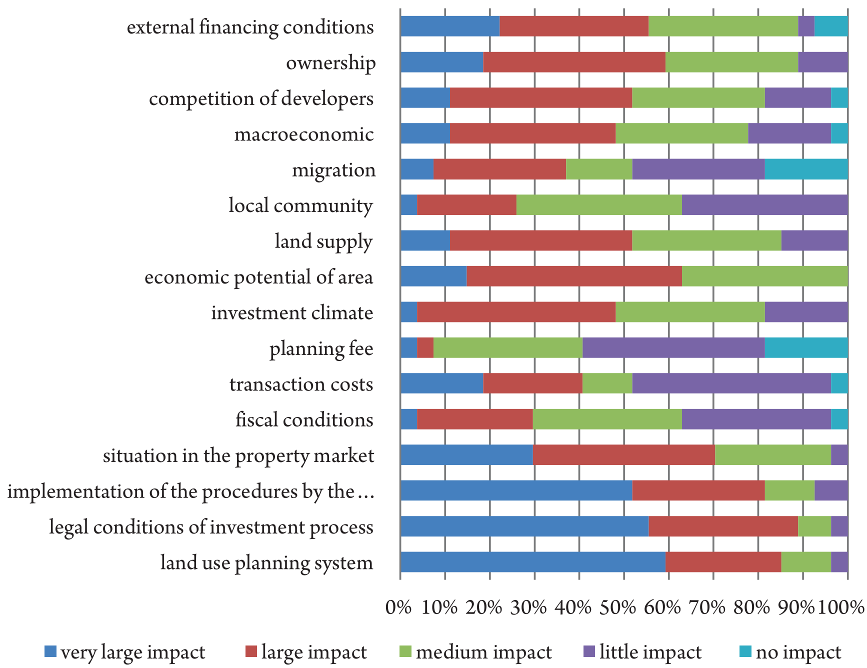

Fig. 2. Structure of the impact of external determinants on land developers' activity (source: own study based on the research)

The average rating for internal factors is 3.28; thus, there is more than mid – score. The highest rates were for business strategy and financial capital resource, together receiving an average rating of 4.33. The respondents were on for very big influence (almost 43%) of owning of financial capital and for business strategy (nearly 45. While more of the respondents (over 50%) assessed that business strategy has a big influence on land developer's activity. Finally, both of these factors were given the highest ratings of all factors. The next factor which was also rated highly was type of development project and its average rate was 3.85, which meant that it was near to being considered to be very important. In the group of internal determinants having over an average influence on land developer's activity were: company experience (3.77); kind of action in land preparation (3.48); cooperation with company preparing land for construction (3.14). The factors which were assessed below 3.0 were: creation of land banks (2.96); number of employees (2.33); legal form (2.19).

The results are presented in Fig. 3.

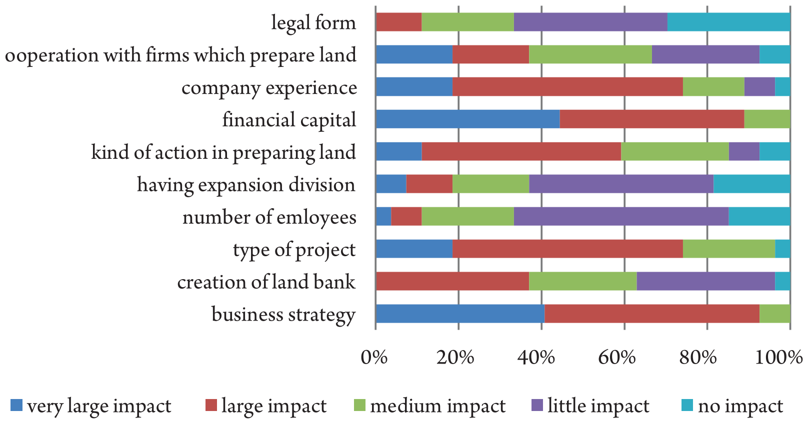

Fig. 3. Structure of the impact of internal determinants (1) on land developers' activity (source: own study based on the research)

The average rating for internal determinants referring to the characteristics of land was 4.0. On this basis, it can be said that respondents considered that the greatest impact on activities depends on the situation related to land. The reason for this may be that of all the analysed determinants, the location was said to be the most important factor of acts related to land preparation for building; this confirmed the intuitive prediction that it would be the primary influence. This is evidenced by the results of the other studies conducted in the context of property development [8]. The informal rule, which appears in various professions in the field of property – location, location, location – was also confirmed [19]. Thus, the location is usually the most important determinant of property value and potential opportunities for sale, such as development projects, especially in difficult market situations. Furthermore, it is based on the investment location, in which investors are subjected to certain external determinants shaped by the municipality/city. The most important of these may include not only the institutional arrangements under the law recognised as a formal periods but especially those that result from the implementation of certain administrative procedures that depend on such the quality and efficiency of public administration. More than 80% of respondents concluded that the impact of location on land developers' activity is very big, a little less than 20% concluded that it is large. Thus, the average rating for this factor was 4.81. The location was assessed to be the most important indicator of all the analysed determinants. Among the factors that were also rated highly and received an average rating above 4.0 were: allocation in zoning plan (4.66); the prices of land considered as the effect of economic and legal and physical characteristics and the current market situation (4.48); the access to the public road observed from physical possibility and legal status (4.4); legal status of property was placed in the fifth with an assessment of 4.37. The set of factors evaluated between 4 and 5 constitute the indicators: the need of obtaining planning permission (4.22); size (4.11); construction type (4.0) Among the factors of which the impact has been assessed as more than mid-score are: neighbourhood/environment which is also related to the location (3.96); shape which can affect the efficiency of the construction project (3.85); amenities are the important position in the economic calculation I'm not sure exactly what you mean by this (3.81) and the soil contamination and the need for its regeneration (3.55).

The graphical portrayal of the abovementioned results is presented in Fig. 4.

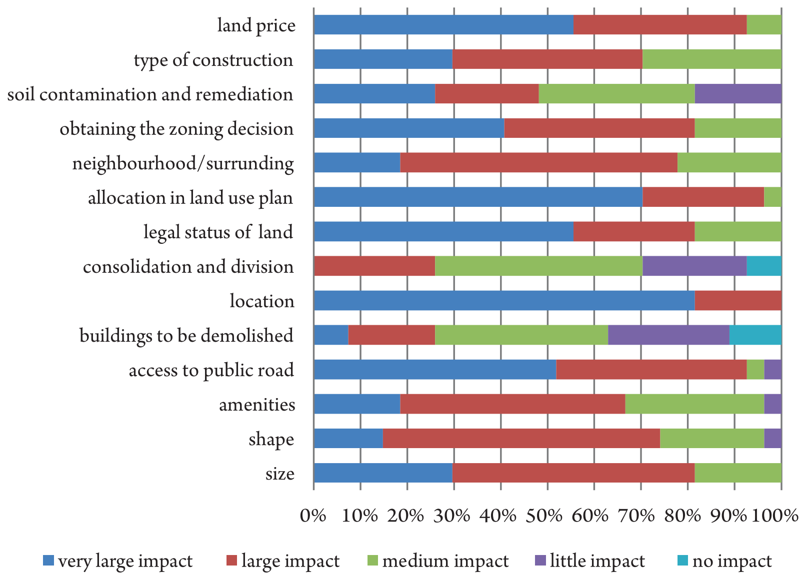

Fig. 4. Structure of the impact of internal determinants (2) on land developers' activity (source: own study based on the research)

In conclusion, of the analysed factors, the most important proved to be location (4.88), allocation in zoning plan (4.67), legal conditions of investment process (4.41).

7. Summary

The analysis of development activity enables the conclusion that the most desirable areas for development projects are urban spaces and suburbs.

The majority of developers make investments in city centres and they use existing technical infrastructure. Thereby, they limit the risk of failure or increasing costs of the project.

The respondents said that the land use planning system is the most important factor of all external determinants. The land development for investment is, to a large extend, subject to applicable planning instruments. The different level of coverage areas by zone plan and feasibility of planning decision applicable for area with no plans cause that a developer has a big influence on the way of construction. Moreover, the consequences are exacerbating problems with regard to the land use planning structure in Poland, the formation of settlements without suitable infrastructure solutions, the devastation of the landscape and the occupation of raw land for residential use while there is still a significant amount of brownfields which could be revitalised.

This study is an important step towards the creation of the concept of developers' activity in preparing land for future construction investment. Often, developers' activity is based on using mainly their own experience and trusting their own judgment, requiring decision making within an environment of high risk and little information, valuing the ability to 'control' the process and make maximum use of interpersonal relationships (with lenders, land use officials, investors, and so on); developers possibly base their activities more on these factors than on good market and feasibility analysis. Yet clearly, development activity represents a large share of the supply side of the property market; thus, it is worthy of attention in spite of the world of uncertainty, imperfect information, and generalised functions within which it exists.

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The reliability of masonry structures – evaluation methods for historical buildings

Niezawodność konstrukcji murowych – metody oceny w budynkach historycznych

Abstract

In this paper, selected issues regarding the assessment of the reliability of masonry structures in existing buildings, including historical buildings, are presented. The specifics of diagnostics and computational analysis of these types of objects are highlighted. Methods of determining the masonry compressive strength in existing structures while taking into account the reliability theory are given. A combination of non-destructive and destructive tests is proposed as the basis for determining the masonry strength parameters. Practical solutions for determination of design masonry strength were given which can be used in assessing the safety of massive brick walls and pillars constituting important structural elements of existing masonry buildings.

Keywords: masonry structures, historical buildings, reliability theory, masonry compressive strength

Streszczenie

W artykule przedstawiono wybrane zagadnienia w zakresie oceny niezawodności konstrukcji murowych w obiektach istniejących w tym obiektach o charakterze historycznym. Wskazano na specyfikę diagnostyki i analiz obliczeniowych tego typu konstrukcji. Podane zostały metody określenia wytrzymałości na ściskanie murów w budynkach istniejących z uwzględnieniem teorii niezawodności konstrukcji. Kompilacja badań nieniszczących i niszczących została zalecona w artykule jako podstawowa metoda w procesie oceny parametrów wytrzymałościowych murów. W artykule podane zostały również praktyczne rozwiązania służące określeniu obliczeniowej wytrzymałości na ściskanie murów, które mogą być wykorzystane przy ocenie bezpieczeństwa masywnych ścian i filarów będących podstawowymi elementami istniejących konstrukcji murowych.

Słowa kluczowe: konstrukcje murowe, budynki historyczne, niezawodność konstrukcji, wytrzymałość muru na ściskanie

1. Introduction

Over the centuries, masonry buildings have been the basic type of buildings erected in cities. Various materials and technologies have been used for their construction. Masonry structures have been erected according to traditional rules passed down and developed by successive generations of builders. As a result of their considerable durability and resistance to fire, many masonry buildings have survived to the present day. Some of these facilities are in good technical condition and continue to successfully perform their functions. If the technical conditions of these buildings are adequate and do not raise any objections, detailed analyses of their structures and the examination of their reliability conditions are not usually necessary. A different situation exists for buildings planned for renovation and reconstruction. In such cases, it is necessary to carry out tests and calculations showing that after the completion of construction, the existing masonry structure can be safely used in its new state.

The masonry walls and pillars subjected to compression are the most important elements of the historical masonry buildings. It is necessary to take into consideration reliability methods to obtain correct compressive strength materials which the structures were erected. Due to the historical character of many masonry facilities, the possibilities for removing an appropriate number of samples are limited. For this reason, the ability to assess masonry strength distribution is also limited. In contrast to concrete structures, there are currently no codes which give procedures that allow identifying the masonry strength of a given structure. This makes the analysis of existing masonry structures very difficult. There are also only a few research works on the determination of the masonry strength of existing structures which take reliability theory into account [1–3].

The considerations presented in this article relate to homogeneous brick masonry in which brick layers are placed in a regular pattern (masonry bond).

2. Basic theory of reliability assessment

The safety and reliability of the structure depends on many factors, firstly, on the type and size of loads and the load-bearing capacity of structural elements. Whether the state of safety is sufficient depends on adherence to the relevant building codes. In codes the requirements in terms of load capacity of cross sections, deformations or displacements of the structure or its fire resistance were given. These requirements take into account the consequences of a failure, for example, the loss of human life and social, economic and environmental consequences.

An acceptable probability level of failure is most often measured in terms of the probability of its occurrence. One of the basic axioms of the reliability theory is the inability to design a structure with a failure probability equal to zero. This involves the adoption of an acceptable probability of failure. The probability of failure (P_f) is determined by the formula:

$$P_f = P\left[g(\mathbf{X}) \leq 0 \right] = \int_{g(\mathbf{X}) \leq 0} f_{\mathbf{X}}(\mathbf{x}) d\mathbf{x} \tag{1}$$

where:

$g(\mathbf{X})$ – performance function,

$\mathbf{x}$ – vector of basic random variables,

$f_{\mathbf{X}}(\cdot)$ – multidimensional function of variables $\mathbf{x}$.

The acceptable failure probability levels proposed in [4] depending on the anticipated failure consequences are presented in Table 1.

Table 1. The failure probability levels recommended in JCSS [4]

Costs	**Failure consequences**		
	Minor	**Average**	**Major**
Large	$P_f \approx 10^{-3}$	$P_f \approx 10^{-4}$	$P_f \approx 10^{-4}$
Medium	$P_f \approx 10^{-4}$	$P_f \approx 10^{-5}$	$P_f \approx 10^{-5}$
Small	$P_f \approx 10^{-5}$	$P_f \approx 10^{-5}$	$P_f \approx 10^{-6}$

The dependence of the acceptable probability of failure for historical buildings (P_f) on their values to society in [1] was proposed. The values of social criterion factors S_c are shown in Table 2.

Table 2. Social criterion factors S_c [1]

Description of the structure	S_c
Historical structures of great importance (e.g. listed by UNESCO)	0.005
Historical structures listed as nationally important	0.05
Historical structures listed as regionally important	0.5
Non-listed historical structures	5

The acceptable probability of failure (P_f) is directly proportional to the factor S_c. Taking into account the recommendations given in Table 2, this means that values of P_f, depending on the historical value of the buildings, may differ by up to a thousandth-fold. The decisions of conservation services and conservation organisations that determine the historical value of the buildings are crucially important in establishing the acceptable probability of failure. It should be noted that the historical value of an object may depend not only on the material value of the engineering work itself, but also on the historical events related to this object that are important to society. For buildings subject to conservation protection, an acceptable probability of failure is proposed at a level of approximately 10^{-6}. This does not apply to historical structures of great importance (e.g. listed by UNESCO), for which P_f values should be determined individually. A significant proportion of masonry buildings are not subject to conservation protection. For these types of structures, it is appropriate to attribute an acceptable level of probability of failure in the range of 10^{-5}–10^{-4}.

The code EN-1990 [5] specifies the acceptable probability of failure depending on the consequences classes of failure (CC3, CC2, CC1) and the reliability classes (RC3, RC2, RC1). The recommendations of the code [5] are presented in Tables 3 and 4. An important safety parameter is the reliability index (β) which is related to the probability of failure by:

$$P_f = \Phi(-\beta) \tag{2}$$

where:

Φ – Laplace function.

The reliability assessment method associated with the reliability index (β) is often called the probabilistic method of Level II.

Table 3. Minimum values for reliability index (ultimate limit states) and maximum values of failure probability according to EN 1990 [5]

Reliability Class	Minimum values for β_{reg}, maximum values of P_f	
	1 year reference period	50 year reference period
RC3	$\beta = 5.2;\ P_f \cong 9.9 \cdot 10^{-8}$	$\beta = 4.3;\ P_f \cong 8.5 \cdot 10^{-6}$
RC2	$\beta = 4.7;\ P_f \cong 1.3 \cdot 10^{-6}$	$\beta = 3.8;\ P_f \cong 7.1 \cdot 10^{-5}$
RC1	$\beta = 4.2;\ P_f \cong 1.2 \cdot 10^{-5}$	$\beta = 3.3;\ P_f \cong 4.8 \cdot 10^{-4}$

Table 4. Definition of consequences classes according to EN 1990 [5]

Consequences class	Description	Examples of buildings and civil engineering works
CC3	**High** consequences for loss of human life, or economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high
CC2	**Medium** consequences for loss of human life, economic, social or environmental consequence **considerable**	Residential and office buildings, public buildings where consequences of failure are medium
CC1	**Low** consequences for loss of human life, and economic, social or environmental consequences **small or negligible**	Agricultural buildings where people do not enter (e.g. storage buildings), greenhouses

The recommendations given in Tables 2 and 3 indicate that most existing masonry buildings can be classified to consequences class of failure CC3 or CC2. The consequences of failure for historical buildings should be considered, not only for material reasons or for loss of human life (as given in Table 4), but also for the consequences related to the loss of the historical value of the object itself.

The vector **F** of random structure failure events is defined in the form of a function:

$$\mathbf{F} = \{g(\mathbf{x}) \leq 0\} \tag{3}$$

where:

$g(\mathbf{x})$ – a performance function:

$$g(\mathbf{x}) = R(\mathbf{x}) - E(\mathbf{x}) \tag{4}$$

where:

$R(\mathbf{x})$ – the resistance,
$E(\mathbf{x})$ – the effect of actions,
$R(\mathbf{x}), E(\mathbf{x})$ – random variables.

The structure is considered to survive if:

$$g = R - E \geq 0 \tag{5}$$

The criterion of reliability of the structure in the probabilistic method of Level II can be written by comparing the design resistance (R_d) and the design value of action effects (E_d):

$$R_d \geq E_d \tag{6}$$

Taking into account the reliability index (β), formula (6) can be transformed into the following form:

$$R_d = \mu_R - \beta_R \sigma_R \geq \mu_E + \beta_E \sigma_E \tag{7}$$

where:

$\beta_R = \beta|\alpha_R|, \ \beta_E = \beta|\alpha_E|$

α_R, α_E – the values of sensitivity factors for resistance and action effects, respectively.

Formula (7) is represented in graph form in Fig. 1.

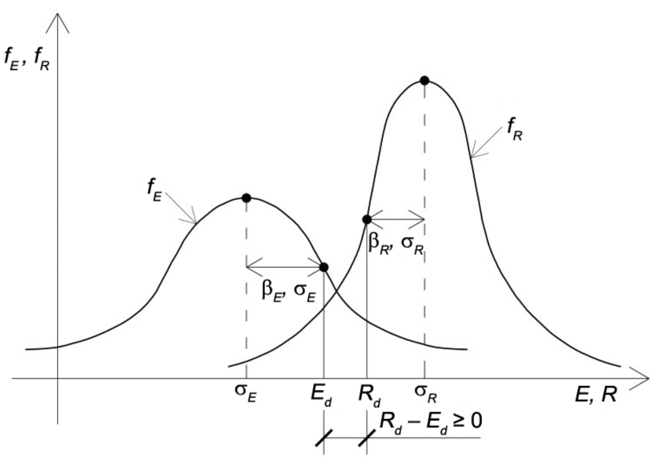

Fig. 1. Load effect (f_E) and resistance probability (f_R) density functions

The design resistance R_d can be expressed in the following form:

$$R_d = \frac{1}{\gamma_{Rd}} R(X_d; a_d) = \frac{1}{\gamma_{Rd}} R\left(\eta \frac{X_k}{\gamma_m}; a_d\right) \tag{8}$$

where:

X_d – the design value of material property,
X_k – the characteristic value of material property,
γ_{Rd} – the partial factor covering uncertainty in the resistance model,
η – the conversion factor,
γ_m – the partial factor for the material property,
a_d – the design value of geometrical data.

Assuming that:

$$\gamma_{Rd}\gamma_m = \gamma_M \tag{9}$$

the design resistance R_d can be obtained as follows:

$$R_d = R\left(\eta\frac{X_k}{\gamma_M};a_d\right) \tag{10}$$

The basic task in the analysis of masonry structures is to determine the load-bearing capacity of walls and pillars subjected to compressive loads. In equation (10), the parameter of the material determining the resistance of the wall or pillar is therefore the masonry compressive strength ($X_k = f_k$; $X_d = f_d$). The design value of the compressive strength of masonry (f_d) is:

$$f_d = \eta\frac{f_k}{\gamma_M} \tag{11}$$

Methods of determining the characteristic compressive strength of the masonry (f_k) and the value of the partial safety factor (γ_M) are provided in code EN 1996-1-1 [6]. However, this code applies only to masonry structures designed and erected today. Currently, there are no codes on how to determine the masonry strength of existing facilities, which makes analysis of these types of structures very difficult.

In code EN 1996-1 [6] it is recommended that the values of the partial safety factor (γ_M) should be determined on the basis of classes related to execution control, the type of mortar assumed in the project and the category of bricks planned to be used in the masonry. This factor, therefore, first of all captures the difference between the strengths of the masonry selected in the design and the masonry that can be found in the structure. For the analysis of existing structures, the situation is completely different. The safety factor should be determined on the basis of the test results and should factor in the uncertainty resulting from the limitations of the applied research methods.

3. Determination of the masonry compressive strength based on laboratory and in-situ tests

The most reliable method to determine the masonry strength in an existing building is testing masonry samples cut from the structure. However, it is rarely possible to take masonry samples of sufficiently large dimensions (Fig. 2a) which are the most representative from massive brick walls or pillars. The collection of such samples causes significant damage to the masonry structure and decreases its bearing capacity. Such large instances of damage to the structures are also unacceptable for conservation reasons. Therefore, it is best to try to determine the masonry strength on samples made in the laboratory using materials with characteristics similar to those from which the structures were constructed. Research of these samples, however, may give false results, because it is extremely difficult to apply modern technologies to recreate original brick masonry erected several dozen or several hundred years ago. Historical bricks formed and fired in a specific way are definitely different from bricks produced today, even if they have similar compressive strengths. Similarly, historical mortars were made from binders and additives which are currently difficult to precisely define and precisely reproduce.

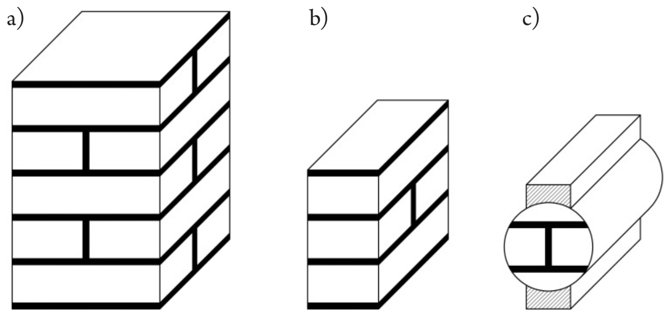

Fig. 2. Samples cut from the structure to determine masonry compressive strength: a) masonry pillars; b) masonry prisms; c) cylindrical samples (150 mm diameter)

For this reason, the basic method to identify the masonry strength is testing performed on original material samples taken from the structure. Most often, smaller samples (prismatic or cylindrical) are cut from the masonry walls (Fig. 2b, c). Due to the dimensions of small samples and the method of applying load to them, the test results should be recalculated using appropriate correction factors. For example, for core samples with a diameter of 150 mm tested under compression perpendicular to the bed joints (Fig. 2c), the correction factor is 1.8 [7, 8]. The error in assessing the masonry strength depends on the dimensions of the samples and the test method. The processes of cutting out, transporting and preparing masonry samples for testing also have an impact on the test results. The samples cut from masonry made on weak mortars are very sensitive and susceptible to damage during their transport to the laboratory; thus, it is necessary to provide them with adequate protection. Samples that are damaged during transport are not suitable for strength tests as their cohesion has been compromised.

The error (Δ_a) of assessing the average strength of the masonry (f_{mean}) depending on the research methods is estimated to be from 10 to 20% [7, 8]:

$$\Delta_a = \pm\,(0.1 - 0.2) \tag{12}$$

This error also includes differences resulting from the dimensions of the tested masonry samples in relation to the dimensions of the masonry wall or the pillar. As the research shows, the masonry strength determined on whole walls is less than the strength estimated on the basis of tests of cylindrical samples or small masonry prisms [1, 8]. A minimum of 3 samples cut from masonry should be tested. With a larger sample size ($n > 3$) it is possible to more precisely determine the mean compressive strength of the masonry (f_{mean}) and the coefficient of variation of masonry strength (V_f). If the number of samples taken from the structure is small, complementary non-destructive tests (NDT) are very important. Firstly, NDT can provide an impression of the homogeneity of the wall. These tests do not cause damage to the masonry structure. They can therefore be conducted in many places. The size of tests is only limited in such cases by the availability of the structure and the costs of the research. The ultrasonic pulse method (UPM), the infrared thermography method (IRT) and tests using geo-radar (GPR) provide the best results in determining the homogeneity of masonry. The Schmidt hammer can also be used for the preliminary assessment of wall homogeneity in external layers, whereas the impact-echo method (IEM) can be used to search for discontinuity of the masonry structure (e.g. cracks and scratches). The choice of research methods depends on many factors and should be made by the expert, in relation to the specific objectives, after a preliminary visual assessment of the structure.

If it is not possible to cut out masonry samples from the existing structure, masonry strength can be estimated using the flat-jack method [9, 10, 11]. In the first step, the mortar from two bed joints is removed; flat jacks are then placed in these joints. The increase of pressure in the flat jacks causes loading of the masonry between them. The disadvantage of this method is local damage to the tested wall. For this reason, the flat-jack method is rarely used to assess masonry strength. However, this method is often used to determine the masonry modulus of elasticity and the level of compressive stress in walls and pillars. The error in assessment of the masonry strength using the flat-jack method is estimated to be around 20%.

The effect of the laboratory and in-situ tests is the identification of the distribution of the masonry strength. The characteristic value of masonry compression strength, understood as 5% quantile, is determined in the case of normal distribution from formula:

$$f_k = f_{mean}\left(1 - k_n V_f\right) \tag{13}$$

If the distribution of the masonry compressive strength is log-normal, the characteristic value of the masonry compressive strength is:

$$f_k = \frac{f_{mean}}{\sqrt{1+V_f^2}} \exp[-k_n V_f] \tag{14}$$

where:

k_n – a factor dependent upon the sample size,

f_{mean} – mean masonry strength:

$$f_{mean} = \frac{1}{n}\sum_{i=1}^{n} f_i \tag{15}$$

Values of k_n according to code EN 1990 [5] are presented in Table 4.

Table 5. Values of k_n for the 5% characteristic value

N	3	4	5	6	10	20	∞
k_n	1.89 (3.37)	1.83 (2.63)	1.80 (2.33)	1.77 (2.18)	1.72 (1.92)	1.68 (1.76)	1.64 (1.64)
() values of k_n if V_x unknown							

The reliability index (β) introduced in the probabilistic method of Level II can be used to calibrate partial factors. Assuming as given in [5] the sensitivity factor $\alpha_R = 0.8$ for $n \to \infty$ partial factor γ_M can be expressed as follows:

for normal distribution
$$\gamma_M = \gamma_{Rd}\gamma_m = \gamma_{Rd}\eta_d \frac{1-1.64V_f}{1-0.8\beta V_f} \tag{16}$$

for lognormal distribution
$$\gamma_M = \gamma_{Rd}\eta_d \exp[V_f(0.8\beta - 1.64)] \tag{17}$$

where:

η_d – conversion factor strongly dependent upon the type of testing method.

In the current state of testing masonry structures, determining the value of the factor γ_{Rd} which expresses the model error is very difficult. The code [5] recommends for designed structures $\gamma_{Rd} = 1.1$. For existing masonry structures, whose detailed identification is limited, it is proposed to adopt slightly larger values, for example, $\gamma_{Rd} = 1.15$.

It is also difficult to precisely determine the error resulting from tests of the specified type of masonry samples (see Fig. 2). Due to the size of the sample and the way it is loaded, the largest error is made for the samples shown in Fig. 2c. The value of this error is estimated at around 20% ($\Delta_a = 0.2$) and therefore $\eta_d = 1.0 + \Delta_a = 1.2$ can be accepted. Results closest to the real values of the masonry compressive strength are obtained by testing masonry pillars (Fig. 2a, $\eta_d = 1.1$).

The values of the partial factor γ_M for masonry structures in historical buildings classified to reliability classes RC2 (β = 3.8) and RC3 (β = 4.3) are presented in Fig. 3.

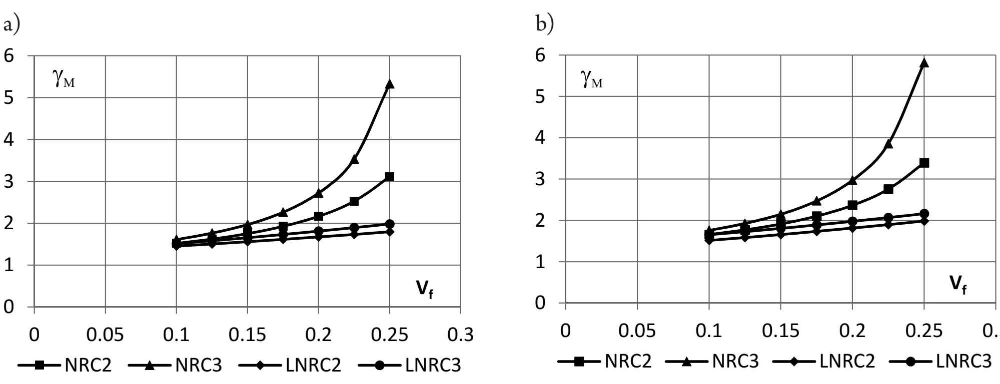

Fig. 3. The partial factor γ_M for historical masonry structures ($n \to \infty$); $\eta_d = 1.1$; b) $\eta_d = 1.2$
NRC2, NRC3 – normal distribution, reliability class RC2 and RC3, respectively;
LNRC2, LNRC3 – lognormal distribution, reliability class RC2 and RC3, respectively

The comparison presented in Fig. 3 shows that the differences between values of γ_M for the RC3 and RC2 reliability classes, especially for masonry characterised by a high coefficient of variation of strength, can be very significant. The proper assessment of an existing facility and the establishment of an appropriate reliability class of the building is therefore a fundamental issue in programming the scope of tests and calculations of the structure. It is also important to assess the type of probability distribution of the masonry compressive strength. In the testing of a historical masonry structure, only a small set of samples can be taken. For this reason, the determination of factor γ_M for a relatively small sample size is of practical importance. In this case, formulas (16) and (17) are changed to the following forms:

$$\gamma_M = \gamma_{Rd}\eta_d \frac{1-k_n V_f}{1-k_{d,n} V_f} \tag{18}$$

$$\gamma_M = \gamma_{Rd}\eta_d \exp[V_f(k_{d,n} - k_n)] \tag{19}$$

The values of $k_{d,n}$ determined for β = 3.8 and β = 4.3 (for 95% confidence level according to SKJ [12]) are shown in Tables 5a and 5b. The values for β = 3.8 are the same as those recommended in the code [5].

Table 5a. Values of $k_{d,n}$ for the ULS design value (β = 3.8)

n	3	4	5	6	10	20	∞
$k_{d,n}$	3.56 (–)	3.44 (11.4)	3.37 (7.85)	3.33 (6.36)	3.23 (4.51)	3.16 (3.64)	3.04 (3.04)
(…) values of $k_{d,n}$ if V_x unknown							

Table 5b. Values of $k_{d,n}$ for the ULS design value (β = 4.3)

n	3	4	5	6	10	20	∞
$k_{d,n}$	4.02 (–)	3.88 (16.5)	3.80 (10.21)	3.76 (7.91)	3.65 (5.41)	3.52 (4.19)	3.44 (3.44)
(…) values of $k_{d,n}$ if V_x unknown							

In laboratory reports, the values of k_n i $k_{d,n}$ for 'V_f known' are generally accepted and could be similarly performed in the case of diagnostic tests. However, the opposite views are also expressed in discussions. Previous studies, the results of which are presented in [1, 2, 13], indicate that the distributions of strength for masonry as well as for bricks and mortars are in the form of log-normal distributions. A summary of the calculation results based on formula (19) are shown in Tables 6a, 6b, 6c and 6d.

Table 6a. Values of partial factor γ_M ($\beta = 3.8$; V_f known)

V_f	*n*						
	3	**4**	**5**	**6**	**10**	**20**	**∞**
0.100	1.50 (1.63)	1.49 (1.62)	1.48 (1.61)	1.48 (1.61)	1.47 (1.61)	1.47 (1.60)	1.46 (1.59)
0.125	1.56 (1.70)	1.55 (1.69)	1.54 (1.68)	1.54 (1.68)	1.53 (1.67)	1.52 (1.66)	1.51 (1.64)
0.150	1.63 (1.77)	1.61 (1.76)	1.60 (1.75)	1.60 (1.74)	1.59 (1.73)	1.58 (1.72)	1.56 (1.70)
0.175	1.69 (1.85)	1.68 (1.83)	1.67 (1.82)	1.66 (1.81)	1.65 (1.80)	1.64 (1.79)	1.62 (1.76)
0.200	1.77 (1.93)	1.75 (1.90)	1.73 (1.89)	1.73 (1.89)	1.71 (1.87)	1.70 (1.86)	1.67 (1.83)
0.225	1.84 (2.01)	1.82 (1.98)	1.80 (1.96)	1.80 (1.96)	1.78 (1.94)	1.77 (1.93)	1.73 (1.89)
0.250	1.92 (2.10)	1.89 (2.06)	1.87 (2.04)	1.87 (2.04)	1.85 (2.01)	1.83 (2.00)	1.80 (1.96)
(…) values of γ_M for $\eta_d = 1.2$							

Table 6b – Values of partial factor γ_M ($\beta = 4.3$; V_f known)

V_f	*n*						
	3	**4**	**5**	**6**	**10**	**20**	**∞**
0.100	1.57 (1.71)	1.55 (1.69)	1.55 (1.69)	1.54 (1.68)	1.53 (1.67)	1.52 (1.66)	1.52 (1.65)
0.125	1.65 (1.80)	1.64 (1.78)	1.62 (1.77)	1.62 (1.77)	1.61 (1.76)	1.59 (1.74)	1.55 (1.73)
0.150	1.74 (1.90)	1.72 (1.88)	1.71 (1.86)	1.71 (1.86)	1.69 (1.84)	1.67 (1.82)	1.66 (1.81)
0.175	1.84 (2.00)	1.81 (1.98)	1.80 (1.96)	1.79 (1.96)	1.77 (1.93)	1.75 (1.91)	1.73 (1.89)
0.200	1.94 (2.11)	1.91 (2.08)	1.89 (2.06)	1.88 (2.05)	1.86 (2.03)	1.83 (1.99)	1.81 (1.98)
0.225	2.04 (2.23)	2.01 (2.19)	1.98 (2.16)	1.98 (2.16)	1.95 (2.13)	1.91 (2.09)	1.90 (2.07)
0.250	2.16 (2.35)	2.11 (2.30)	2.09 (2.28)	2.08 (2.27)	2.05 (2.26)	2.00 (2.19)	1.94 (2.16)
(…) values of γ_M for $\eta_d = 1.2$							

Table 6c. Values of partial factor γ_M ($\beta = 3.8$; V_f unknown)

V_f	*n*						
	3	**4**	**5**	**6**	**10**	**20**	**∞**
0.100	–	2.40 (3.04)	2.20 (2.40)	1.92 (2.10)	1.64 (1.79)	1.53 (1.67)	1.46 (1.58)
0.125	–	2.99 (3.79)	2.52 (2.75)	2.13 (2.33)	1.75 (1.91)	1.60 (1.75)	1.51 (1.64)
0.150	–	–	2.90 (3.16)	2.37 (2.58)	1.87 (2.04)	1.68 (1.83)	1.56 (1.70)
0.175	–	–	3.32 (3.63)	2.63 (2.87)	1.99 (2.17)	1.75 (1.92)	1.62 (1.76)
0.200	–	–	–	2.92 (3.18)	2.12 (2.32)	1.83 (2.01)	1.67 (1.83)
0.225	–	–	–	3.24 (3.54)	2.27 (2.47)	1.91 (2.11)	1.73 (1.89)
0.250	–	–	–	–	2.42 (2.64)	2.00 (2.21)	1.80 (1.96)

Table 6. (...) values of γ_M for $\eta_d = 1.2$

Table 6d – Values of partial factor γ_M ($\beta = 4.3$; V_f unknown)

V_f (cov)	*n*						
	3	**4**	**5**	**6**	**10**	**20**	**∞**
0.100	–	–	2.78 (3.04)	2.24 (2.45)	1.64 (1.79)	1.61 (1.76)	1.52 (1.65)
0.125	–	–	2.68 (3.39)	2.59 (2.82)	1.75 (1.91)	1.71 (1.87)	1.55 (1.73)
0.150	–	–	3.26 (4.13)	2.99 (3.26)	1.87 (2.04)	1.82 (1.99)	1.66 (1.81)
0.175	–	–	–	3.45 (3.76)	1.99 (2.17)	1.94 (2.11)	1.73 (1.89)
0.200	–	–	–	3.99 (4.34)	2.12 (2.32)	2.06 (2.24)	1.81 (1.98)
0.225	–	–	–	–	2.27 (2.47)	2.19 (2.38)	1.90 (2.07)
0.250	–	–	–	–	2.42 (2.64)	2.32 (2.53)	1.94 (2.16)

(...) values of γ_M for $\eta_d = 1.2$

The above data shows the dependence of the value of partial factor γ_M on the sample size. This relationship is particularly clear for masonry characterised by a high variability of strength characteristics. For this type of masonry, the estimation of the partial factor γ_M should be based on the testing of a large number of samples. If it is not possible to take a sufficiently large number of samples, supplementary non-destructive tests should be provided. Non-destructive tests should also be performed in places where samples for destructive testing are to be later cut out in order to determine appropriate correlation coefficients. The combination of non-destructive and destructive tests is the basic method for determining the masonry strength and the coefficient of variation for this parameter [8, 9].

If the partial factor γ_M is determined taking into account the test results on a small sample size, the values of this factor can be significantly higher than three and therefore greater than the maximum value of γ_M given for contemporary masonry structures in code [6].

The values of factor γ_M given in Tables 6a, 6b, 6c and 6d are in the range of approx. 1.5 to approx. 4.3. It should be emphasised that these values are appropriate for brick masonry which has a COV of not more than 0.25. It should also be remembered that the masonry strength determined on the samples cut out of the structure and possibly based on supplementary non-destructive tests refer to places that constitute a small part of the masonry structure. Therefore, the final values of the partial factor γ_M should depend on the decision of the expert performing the structural analysis. The values of γ_M given in this chapter should be treated as auxiliary in such analyses.

4. Determination of the masonry compressive strength based on the strength of bricks and mortar

Assessment of the masonry compressive strength based on the tests of masonry samples cut out of the structure is a labour-intensive method requiring the involvement of specialist equipment and people with extensive experience in conducting research on masonry structures. Attempts are also made to assess masonry strength based on strength tests of bricks and mortar. For example, a power relationship is used in which the compressive strength of the wall (f) is a function of the compressive strength of the bricks (f_B) and the compressive strength of the mortar (f_M):

$$f = A \cdot f_B^u \cdot f_M^w \tag{20}$$

where:

A, u, w – constants.

This form also has the formula given in code EN 1996-1-1 [6]:

$$f_k = K \cdot f_b^{0.7} \cdot f_m^{0.3} \tag{21}$$

where:

f_k – characteristic compressive strength of masonry;
f_b – normalised compressive strength of masonry units (bricks);
f_m – mortar compressive strength;
K – constant.

The characteristic strength of masonry determined from formula (21) is a function of the mean brick compressive strength and the mean mortar compressive strength determined in the tests. The test procedures are given in the relevant codes [16, 17]. Formula (21) is an empirical relation and has been determined based on extensive experimental studies. The dimension of the constant K is chosen so that the final result of the masonry strength calculations is in MPa. For brick masonry, in code EN 1996-1-1 [6] a value of K equal to 0.55 was adopted. This value applies to brick masonry without longitudinal joints. For masonry with longitudinal joints, the code EN 1996-1-1 [6] recommends a reduction of the K coefficient by 20%, hence $K = 0.46$. It should be noted that the recommendations of EN 1996-1-1 [6] apply to constructions designed from modern materials. For masonry structures erected several dozen or several hundred years ago made on weak mortars, the use of formula (16) requires additional reduction factors [8].

From formula (21), the characteristic compressive strength of masonry is obtained on the basis of the mean strength of bricks and the mean strength of mortar, i.e. deterministic parameters. This is due to the fact that until now, it has not been determined to what extent the brick strength variability and the mortar strength variability affect masonry strength. It should also be noted that in the case of existing structures, it is not possible to determine the compressive strength of the mortar in accordance with [17], because samples of dimensions $40 \times 40 \times 160$ mm cannot be cut out of masonry joints, the thickness of which is usually in the range of 10 mm to 25 mm. For this reason, appropriate correction factors should be applied.

The power formula (20) can be treated as a function determining the manner of assigning a random variable f (compressive strength of the masonry) of two random variables: f_B (compressive strength of bricks) and f_M (compressive strength of the mortar). It can be considered that the issue of determining the parameters of the probability distribution of the masonry compressive strength is a function of two random variables with known distributions. If it is assumed that f_B, f_M are independent random variables and have log-normal distributions, then the mean value of the natural logarithm $\ln(f)$ is:

$$\mu_{\ln(f)} = \mu_{\ln(A)} + u\mu_{\ln(f_B)} + w\mu_{\ln(f_M)} \tag{22}$$

while the standard deviation σ of natural logarithm $\ln(f)$ is:

$$\sigma_{\ln(f)} = \sqrt{(u\sigma_{\ln(f_B)})^2 + (w\sigma_{(f_M)})^2} \tag{23}$$

The mean value of random variable $\ln(f)$ and the standard deviation of this random variable can be directly defined based on mean values and standard deviations of the random variables $\ln(f_B)$ and $\ln(f_M)$, provided that the values of material constants A, u and w are known. In [8, 9, 14] and [15], the results of experimental tests on masonry samples cut from existing masonry are given. Based on the analysis of these results, the graph shown in Fig. 4 has been prepared.

Taking in account as recommended by EN 1996-1-1 [6], $u = 0.7$, $w = 0.3$, the value of constant A was obtained with a range of 0.26–0.65 (mean 0.43). The values of constant A were calculated by performing an inverse task, i.e. on the basis of the random variables $\ln(f)$, $\ln(f_B)$ and $\ln(f_M)$ determined in the tests, the value of constant A was calculated. From the graph in Figure 4, increases to the values of constant A can be seen with increasing masonry compressive strengths. For masonry with weak lime and lime-cement mortars, the value of A is about 0.35, while for walls with cement-lime mortars, the values of A are significantly higher. The large variability of the A-value results from, among other factors, the different workmanship of the masonry, although it is difficult to precisely determine this relationship. The detrimental effect of poor workmanship is due to the improper filling of joints. The thickness of joints also plays an important role. If the dimensions of the bricks vary, the dimensions of the mortar joints will also vary. The result is non-uniform joint thicknesses which create bending moments and stress concentrations in the brick. The decrease in the compressive masonry strength due to poor workmanship can be up to 40%.

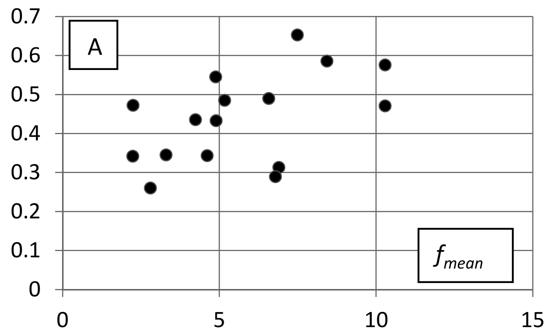

Fig. 4. Values of factor A

Taking into account relationships:

$$\sigma_{\ln(f_B)} = \sqrt{\ln(1+V_{f_B}^2)} \approx V_{f_B} \tag{24}$$

$$\sigma_{\ln(f_M)} = \sqrt{\ln(1+V_{f_M}^2)} \approx V_{f_M} \tag{25}$$

where:

$V_{fB,}$ V_{fM} – coefficients of variation of brick strength and mortar strength, respectively, a formula to determine the coefficient of variation of the masonry strength (V_f) can be obtained:

$$V_f = \sqrt{(uV_{f_B})^2 + \left(wV_{f_M}\right)^2} \tag{26}$$

A comparison of the calculations made using formula (26) with the results of experimental tests (V_f^*) are shown in Fig. 5. The values of parameters u and w were adopted in accordance with EN 1996, $u = 0.7$, $w = 0.3$.

Differences in the values of the COV calculated from formula (26) with values obtained from experimental studies can be significant (up to 60%). This is due to the fact that it is not only the coefficients of variation of bricks strength and mortar strength that have a significant impact on the coefficient of variation of masonry strength in the structure. In [18], it was stated that the workmanship of the masonry is of fundamental importance for the COV of masonry strength, while the other parameters are of secondary importance. This issue requires further research and analysis. It should also be emphasised that determining the workmanship of masonry based only on visual inspection of the structure in the external layers may lead to incorrect applications. As a rule, non-plastified brick facing layers were made more thoroughly than the rest of the masonry wall.

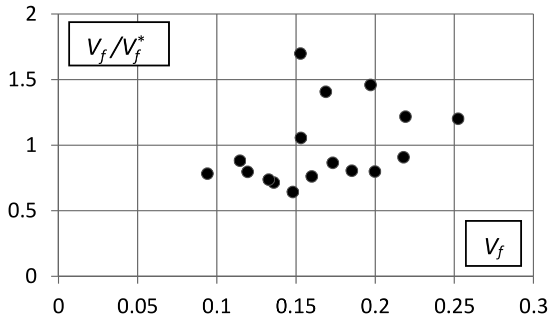

Fig. 5. Coefficient of variation (COV) of the masonry strength – comparison of test results (V_f^*) according to [8, 9, 13] and [14] and results of calculations (V_f) based on formula (26)

COV of masonry strength determined in experimental tests on samples cut from the structure were in the range of:

$$V_f^* = 0.12–0.24 \tag{27}$$

while calculated on the basis of formula (26):

$$V_f = 0.10–0.25 \tag{28}$$

The mean values of COV of masonry strength obtained from experimental investigations given in [8, 9, 14] and [15] and calculations based on formula (26) are:

$$V_{f,mean}^* = 0.178 \tag{29}$$

$$V_{f,mean} = 0.166 \tag{30}$$

The difference between $V_{f,mean}^*$ and V_{fmean} is not significant and amounts to 7%.

The function of probability distribution of the masonry compressive strength and the parameters of this function determined on the basis of formulas (24) and (25) can be used in the structural reliability analysis. In practice, the use of this method requires the testing of an appropriate number of samples of bricks and mortar, which is a prerequisite for determining the strength distributions of masonry components. The Austrian code [19] requires that this assessment should be based on brick and mortar tests in three places of the analysed section of the structure, whereby at least five samples of bricks and ten samples of mortar should be taken at each place. The samples should be representative of the entire section of the structure, so they should also be taken from internal layers of masonry walls or pillars. This is not a simple matter from a technical point of view.

For this reason, in determining the compressive masonry strength based on the strength of bricks and mortar, high partial factors should be applied ($\gamma_M \geq 2.5$).

5. Summary

In the paper, selected issues related to determining the compressive strength of masonry in existing structures, taking into account the reliability theory, have been presented. The research methods and methods for analysing their results used in determining the basic parameters of the probability distributions of masonry strength have been given. The methodology of test methods on samples cut from masonry and non-destructive testing methods have been discussed. Specifics have been highlighted with respect to performing this research on existing masonry structures, including historical structures. On the basis of the conducted analysis, a method for determining the masonry strength and the partial factor (γ_M) in existing facilities has been proposed.

The method of determining masonry compressive strength based on strength tests of bricks and mortar was also presented. The power formula was used, in which the compressive strength of masonry is a function of the compressive strength of bricks and the compressive strength of mortar.

The presented solutions can be used in practice in the analysis of walls and pillars constituting the basic structural elements of existing masonry buildings.

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Usage of a zero-sum differential game in the optimal control of an object described by a nonlinear model

Wykorzystanie gry różniczkowej o sumie zerowej w optymalnym sterowaniu obiektem opisanym modelem nieliniowym

Abstract

This article presents the usage of a zero-sum differential game to control a nonlinear object, which, in the analysed problem, was a mathematical pendulum. The obtained control was optimal with regard to adopted quality indicator for the worst interference. The two-point boundary value problem was solved numerically by means of the Dircol software application. Numerical solutions, meeting all the necessary optimality conditions, were obtained for different values of the rough parameter and for different values of damping.

Keywords: robust control, optimal control, two-point boundary value problem, minimum principle

Streszczenie

W artykule wykorzystano grę różniczkową o sumie zerowej do sterowania obiektem nieliniowym, jakim w analizowanym problemie jest wahadło matematyczne. Uzyskano sterowanie optymalne ze względu na przyjęty wskaźnik jakości, przy najgorszym zakłóceniu. Dwupunktowy problem brzegowy został rozwiązany numerycznie przy wykorzystaniu programu Dircol. Rozwiązania numeryczne spełniające wszystkie warunki konieczne optymalności zostały otrzymane dla różnych wartości parametru szorstkości oraz przy różnych wartościach tłumienia.

Słowa kluczowe: sterowanie typu robust, optymalne sterowanie, dwupunktowy problem brzegowy, zasada mimimum

1. Introduction

Structure control and regulation problems should take into account different criteria. One of the crucial criteria is the stability of control, specifically the expectation that a dynamic system is near its ideal state or is approaching it. Optimisation with regard to the chosen objective function is also significant requirement for different technical issues. The formal description of such criteria within the confines of modelling is an element of the present study.

In this paper, we deal with the optimal robust control. Unknown and unpredictable interferences are analysed; however, their influence on system dynamics is known. A well-designed rough process must be capable of limiting interferences, but at the same time, can be very far from the optimal solution. However, there exists a certain concept of compromise between optimality and roughness. A differential game with the null sum can be use in the robust-optimal control, which leads to a saddle point problem.

2. Dissipative systems controlled optimally

Let us consider the following dynamical dissipative system [10]:

$$\begin{aligned} x' &= f(x,u(x),w) \\ v &= l(x,u(x),w) \end{aligned} \tag{1}$$

with the control $u \in U \subset L_2^{n_u}$ and the interference $w \in W \subset L_2^{n_w}$.

System (1) is dissipative if functions S, s exist with the following properties:

$$S(x(t_1)) < S(x(t_0)) + \int_{t_0}^{t_1} s(w,v)dt \tag{2}$$

for all $w \in W$ and $t > t_0$.

The choice $s(w,v) = \gamma^2 \|w\|^2 - \|v\|^2$ leads to the limited strengthened stable system L_2.

The expression (3) satisfies property (2).

$$S^*(x,u) = \max_{w \in W,\, t_1 > t_0} \int_{t_0}^{t_1} \left\{ \|l(x,u,w)\|^2 - \gamma^2 \|w\|^2 \right\} dt \tag{3}$$

In addition to the system's dissipativity, the robust type optimal control $u^* = u^*(x)$ should provide potentially good optimal properties, which means that u should be chosen for arbitrary interferences w such that:

$$\begin{aligned} J(x,u) &= \int_{t_0}^{t_f} \|l(x,u,w)\|^2 dt \quad \Rightarrow \quad \min \\ l(x,u,w) &= \|l(x,u,w)\|^2 \end{aligned} \tag{4}$$

If we assume a pessimistic interference in the system controlled by u^*, we obtain:

$$S^*(x,u^*)=\max_w \min_u \int_{t_0}^{t_f}\left\{ \left\|l(x(t),\, u(x(t)),w(t)\right\|^2 -\gamma^2 \left\|w(t)\right\|^2 \right\} dt \tag{5}$$

and thus, the saddle point for problem (4) is described by functional [5]:

$$J(x,u,w)=\int_{t_0}^{t_f}\left\{ \left\|l(x(t),\, u(x(t)),w(t))\right\|^2 -\gamma^2 \left\|w(t)\right\|^2 \right\} dt \quad \Rightarrow \quad \max_w \quad \min_u \tag{6}$$

The form of quality indicator (6) results from the dissipative systems theory.

Remarks:

1. Control u^* guarantees the roughness of the system. Optimal properties resulting from the minimisation of functional (4) play a secondary role. The degree of roughness represented by parameter γ indirectly describes the value of the functional (the rougher the system is, the less optimal it is).
2. The sequence of mathematical operations, specifically min and max, occurring in (6) is important. Swapping these operations can facilitate the obtaining of the solution considerably.
3. Parameter γ indirectly gives information on the dynamic system. The optimisation of roughness is very important $\gamma^* = \inf\{\gamma\}$.

The optimisation of roughness is the fundamental task. The saddle point for functional (6) can be determined for a given $\gamma \in R^+$. The determination of γ^* can be approximated by the strategy γ.

The formulation of the min/max problem (6) can be interpreted as a two-player differential game. A two-player zero-sum differential game is described by:

1. The two players who are represented by u, w, which in the time interval $[t_{0,}\ t_f]$ influence the dynamic system

$$\begin{aligned} &x' = f(x,\, u,\, w) \\ &x(t_0)=x_0, \quad r(x(t_f))=0 \\ &u(t)\in U, \quad \forall \quad t\in[t_0,\, t_f] \\ &w(t)\in W, \quad \forall \quad t\in[t_0,\, t_f] \end{aligned} \tag{7}$$

where $f \in C^1(R^{n_x}\times R^{n_u}\times R^{n_w},\, R^{n_x})$, $r\in C^1(R^{n_x},\, R^{n_r})$, $u\subset R^{n_u}$, $w\subset R^{n_w}$, $x\subset X$;

2. The functional

$$J(x,u,w)=\int_{t_0}^{t_f} l(x(t),\, u(t),\, w(t))dt \quad \Rightarrow \quad \max_w \quad \min_u \tag{8}$$

where $l\in C^1(R^{n_x}\times R^{n_u}\times R^{n_w},\, R)$.

3. The strategy class $u=\Gamma^u(t,x)$, $w=\Gamma^w(t,x)$
   Information about the structures of controls $u(t)$, $w(t)$ is significant for solving the saddle problem.
   In the dynamic system, these magnitudes take the roles of players in the differential game and are described by strategies Γ^u, Γ^w.

The fundamental questions are as follows: What strategy should be assumed for rough control $u(t)$? What strategy and interference structure should one account for?

The solution of this game is described by the Nash equilibrium [8].

3. Necessary conditions for the solution of the saddle point problem

Pair (u^*, w^*) defines the saddle point of the zero-sum game if:

$$J(u^*,w)\leq J(u^*,w^*)\leq J(u,w^*) \tag{9}$$

for all allowed strategies $u,\ w\in U\times W$.

Let us define:

$$J^+=\min_u\left\{\max_w J\right\}$$
$$J^-=\max_w\left\{\min_u J\right\}.$$

Using this definition, the quality indicator will be named the value of the zero-sum game

if it satisfies $J^*=J^+=J^-$.

The problem of the zero-sum differential game can be written down with the Hamilton-Jacobi-Bellman equation:

$$\begin{aligned}0&=\min_u\max_w\frac{\partial J}{\partial x}f(x,\ u,\ w)+l(x,\ u,\ w)\\&=\max_w\min_u\frac{\partial J}{\partial x}f(x,\ u,\ w)+l(x,\ u,\ w)\end{aligned} \tag{10}$$

The general solution of this partial equation provides the sought controls. It is worth noting that the solution can be obtained only for simple systems with small dimension of the state space.

If the formalism of the minimum principle is used for the problem described by equations (1–6), the necessary conditions for optimality can be set together:

Let the Hamilton function be defined:

$$H(x,\ \lambda,\ u,\ w)=\lambda^T\cdot f(x,\ u,\ w)+l(x,\ u,\ w)-\gamma^2\cdot w^2 \tag{11}$$

then the boundary problem takes the form (12).

$$
\begin{aligned}
&x' = f(x, u, w)\\
&\lambda' = -\left.\frac{\partial f}{\partial x}\right|^T (x, u^*, w^*)\cdot\lambda - \left.\frac{\partial l}{\partial x}\right|^T (x, u^*, w^*)\\
&x(0) = x_0, \quad x(t_f) = 0, \quad H(x, \lambda, u, w)\big|_{t_f} = 0\\
&u^* = \arg\min_{u\in U} H(x, \lambda, u, w^*)\\
&w^* = \arg\max_{w\in W} H(x, \lambda, u^*, w)\\
&\frac{\partial^2 H}{\partial u^2} > 0 \quad \frac{\partial^2 H}{\partial w^2} < 0 \quad \frac{\partial^2 H}{\partial u \partial w} = 0
\end{aligned} \tag{12}
$$

In order to determine the saddle point, we have to continuously solve the canonical system of differential equations (12) and thus have assured access to control u^* and interference w^*. The determination of saddle points in technical applications are thoroughly described in works [2, 3, 7].

According to the suggestion from [1], if the worst interference $w = w^*$ is assumed, control u is determined, such that it minimises the given functional (13) by including functions λ_1, λ_2 in state variables.

$$
\int_{t_0}^{t_1} (l(x, u, w^*) - \gamma^2 w^{*2})dt \quad \to \quad \min_u \tag{13}
$$

The system of equations for the determination of interference w^* has the following form [6]:

$$
\begin{aligned}
&x' = f(x, u, w^*)\\
&\lambda' = -\left.\frac{\partial f}{\partial x}\right|^T (x, u, w^*)\cdot\lambda - \left.\frac{\partial l}{\partial x}\right|^T (x, u, w^*)\\
&w^* = \arg\max_{w\in W} H(x, \lambda, u, w)\\
&u \in U, \quad x(0) = 0, \quad x(t_f) = 0, \quad H(x, \lambda, u, w^*)(t_f) = 0\\
&H(x, \lambda, u, w) = \lambda^T \cdot f(x, u, w) + l(x, u, w) - \gamma^2 \cdot w^2
\end{aligned} \tag{14}
$$

Assuming that $w \in L_2^{n_w}$ and taking into consideration condition (14)

$$
\frac{\partial H}{\partial w} = \frac{\partial f}{\partial w}(x, u, w^*)\cdot\lambda + \frac{\partial l}{\partial w}(x, u, w^*) - 2\gamma^2 \cdot w = 0, \tag{15}
$$

function $w^* = w^*(x, \lambda)$ is obtained.

In the next step, the state vector will have the form: (x, λ). Accordingly, the Hamilton function and the conditions for the determination of u^* can now be written as:

$$
\begin{aligned}
&H_{new}(x, \lambda, \psi, \theta) = \psi^T \cdot f(x, u, w^*) + \theta^T \lambda'(x, u, w^*) + l(x, u, w^*) - \gamma^2 \cdot w^{*2} \\
&\theta' = -\frac{\partial H_{new}}{\partial \lambda} \\
&\psi' = -\frac{\partial H_{new}}{\partial x} \\
&u^* = \arg\min_{u \in U} H_{new}(x, \lambda, \psi, \theta, w^*)
\end{aligned} \tag{16}
$$

4. Controlled and interfered movement of the mathematical pendulum

Let us consider a physical system (the mathematical pendulum) consisting of a concentrated mass $m = 1$ attached to a weightless member of length $l = 1$. Let it be assumed that the dissipation of energy is in the bearing with a linear relation of the dumping moment on the angular velocity. Additionally, interference w and control u are introduced. The optimisation problem is thus formulated as follows:

Functional (17) is minimised:

$$
\int_0^{t_f} (u^2 + x_2^2 - \gamma^2 w^{*2}) dt \quad \Rightarrow \quad \min \tag{17}
$$

with the limitations:

$$
\begin{aligned}
&x_1' = x_2 \\
&x_2' = -(ax_2 + b\sin x_1) - u\cos x_1 + w^* \cos x_1
\end{aligned} \tag{18}
$$

and for which w^* is determined from the condition:

$$
\begin{aligned}
&H = \lambda_1 x_2 - \lambda_2 (ax_2 + b\sin x_1) - \lambda_2 u \cos x_1 + \lambda_2 w^* \cos x_1 + (u^2 + x_2^2 - \gamma^2 w^{*2}) \\
&\frac{\partial H}{\partial w^*} \to \lambda_2 \cos x_1 - 2\gamma^2 w^* = 0 \\
&w^* = \frac{\lambda_2 \cos x_1}{2\gamma^2} \\
&\lambda_1' = -\frac{\partial H}{\partial x_1} = \lambda_2 b \cos x_1 + \lambda_2 w^* \sin x_1 - \lambda_2 u \sin x_1 \\
&\lambda_2' = -\frac{\partial H}{\partial x_2} = a\lambda_2 - \lambda_1 - 2x_2
\end{aligned} \tag{19}
$$

If we denote $\lambda_1 = x_4$, $\lambda_2 = x_5$, we can write state equations (x^T, λ^T) (19) in the form:

$$
\begin{aligned}
&x_1{}' = x_2 \\
&x_2{}' = -ax_2 - b\sin x_1 - u\cos x_1 + w^{*}\cos x_1 \\
&x_3{}' = u^2 + x_2^2 - \gamma^2 w^{*2} \\
&x_4{}' = bx_5\cos x_1 + w^{*} x_5 \sin x_1 - ux_5\sin x_1 \\
&x_5{}' = -x_4 + ax_5 - 2x_2 \\
&w^{*} = \frac{x_5\cos x_1}{2\gamma^2}
\end{aligned}
\tag{20}
$$

Finally, the system of state equations can be written as follows:

$$
\begin{aligned}
&x_1{}' = x_2 \\
&x_2{}' = -ax_2 - b\sin x_1 - u\cos x_1 + \frac{x_5(\cos x_1)^2}{2\gamma^2} \\
&x_3{}' = u^2 + x_2^2 - \frac{x_5^2(\cos x_1)^2}{4\gamma^2} \\
&x_4{}' = bx_5\cos x_1 + \frac{x_5^2\sin x_1\cos x_1}{2\gamma^2} - ux_5\sin x_1 \\
&x_5{}' = -x_4 + ax_5 - 2x_2
\end{aligned}
\tag{21}
$$

The following boundary conditions apply for state equations (20):

$$
\begin{aligned}
&x_1(0) = x_{10}\,, \quad x_2(0) = x_{20}\,, \\
&x_1(t_f) = 0\,, \quad x_2(t_f) = 0\,, \quad H(t_f) = 0\,, \\
&x_1(t_f)x_5(t_f) - x_1(t_f)x_4(t_f) = 0\,.
\end{aligned}
\tag{22}
$$

The boundary conditions for functions x_4, x_5 are unknown and the final time t_f will be determined from the condition $H(t_f) = \sum_{i=1}^{nx} \lambda_i \cdot x_i{}' + u^2 + x_2^2 - \gamma^2 w^{*2} = 0$.

We can define the Hamilton function for state equations (21) in the following way [4]:

$$
\begin{aligned}
&H = \psi_1 x_2 - \psi_2(ax_2 + b\sin x_1) - \psi_2 u\cos x_1 + \psi_2\frac{x_5(\cos x_1)^2}{2\gamma^2} + \\
&\psi_3\left\{u^2 + x_2^2 - \left[\frac{x^5(\cos x_1)^2}{4\gamma^2}\right]\right\} + \psi_4 bx_5\cos x_1 + \psi_4\frac{x_5^2\sin x_1\cos x_1}{2\gamma^2} - \\
&\psi_4 ux_5\sin x_1 + \psi_5(-x_4 + ax_5 - 2x_2)
\end{aligned}
\tag{23}
$$

The optimal control u is determined from the condition $\frac{\partial H}{\partial u}=0$:

$$
\begin{aligned}
&-\psi_2\cos x_1+2\psi_3 u-\psi_4 x_5\sin x_1=0\\
&u=\frac{\psi_2\cos x_1+\psi_4 x_5\sin x_1}{2\psi_3}
\end{aligned}
\tag{24}
$$

Employing the condition $\psi_i{}'=-\frac{\partial H}{\partial x_i}$, the system of equations for adjoint functions ψ_i can be finally written in the form:

$$
\begin{aligned}
&\psi_1{}'=\psi_2 b(\cos x_1)-\psi_2 u\sin x_1+\frac{\psi_2(\sin 2x_1)}{2\gamma^2}-\psi_2\frac{x_5^2(\sin 2x_1)}{4\gamma^2}+\psi_4 b x_5(\sin x_1)+\\
&-\psi_4{}'\frac{x_5^2(\sin 2x_1)}{2\gamma^2}+\psi_4 u x_5(\cos x_1)\\
&\psi_2{}'=\psi_2 a-2\psi_3 x_2+2\psi_5-\psi_1\\
&\psi_3{}'=0\\
&\psi_4{}'=\psi_5\\
&\psi_5{}'=-\frac{\psi_2(\cos x_1)^2}{2\gamma^2}+\frac{\psi_3 x_5(\cos x_1)^2}{2\gamma^2}-\psi_4 b\cos x_1-\frac{\psi_4 x_5^2(\sin 2x_1)}{2\gamma^2}+\psi_4 u\sin x_1-\psi_5 a
\end{aligned}
\tag{25}
$$

Optimal control $u(t)$ of the robust type minimises functional (17), specifically, variable x_3, and satisfies the extended state equations with optimally determined interference w^*, which in turn, maximises functional (17). State equations (21) and adjoint equations (25) allow determining the optimal control (24) which minimises the objective function.

5. Numerical results

The optimal controls were determined in accordance with the Pontryagin minimum principle. Program Dircol-2.1 [9] was used to numerically solve the problem formulated in the previous section. This required the preparation of input subprograms: user.f, DATDIM, DATLIM in which the state equations, boundary conditions, limitations, objective function and start values were defined. The calculation results were obtained in a graphic form as diagrams, and as a set of data. Solutions meeting all necessary optimality conditions were found for different values of rough parameter and for different values of damping.

Figures 1–4 depict complete solutions of the $\min\limits_u \max\limits_w$ problem: state variables x_i, respective adjoint variables Ψ_i, control u, interference w and the phase diagram $x_2=x_2(x_1)$ for a value of damping established as $a = 1$ and a value of rough parameter of $\gamma = 0.7$.

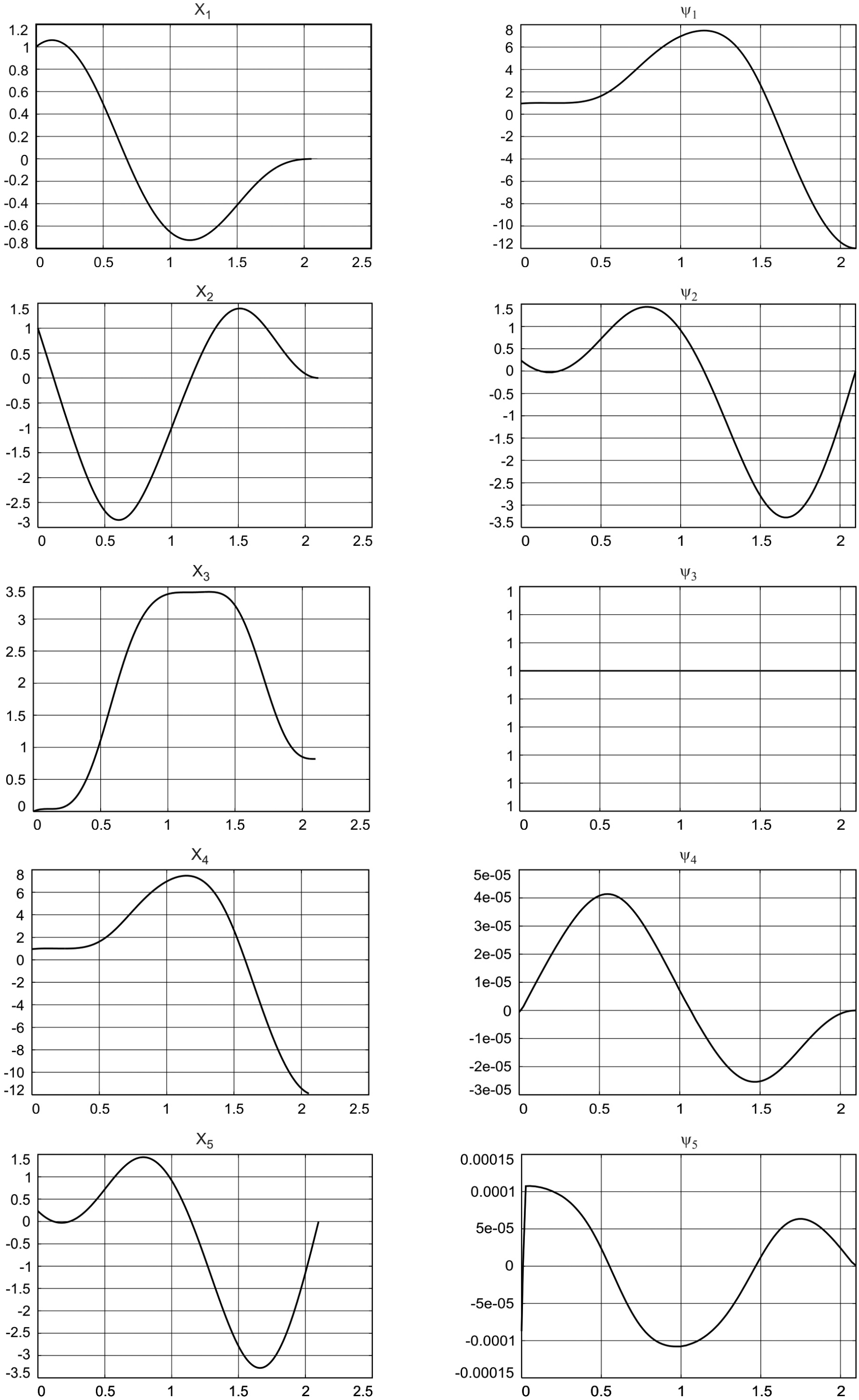

Fig. 1. State variables and corresponding adjoint variables for $a = 1$ and $\gamma = 0.7$

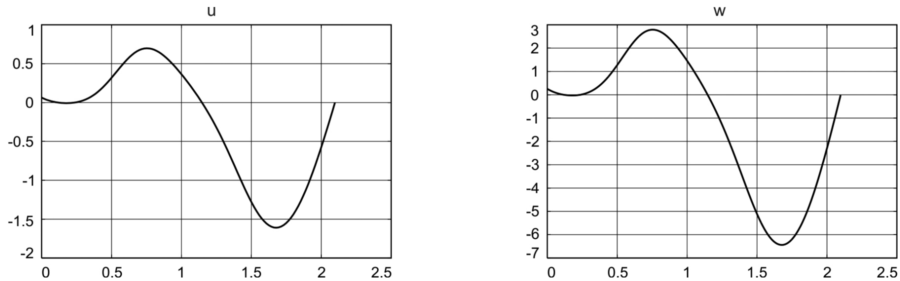

Fig. 2. Control and interference function for $a = 1$ and $\gamma = 0.7$

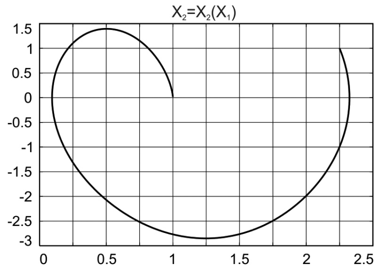

Fig. 3. Diagram X_2 over X_1 in phase-space for $a = 1$ and $\gamma = 0.7$

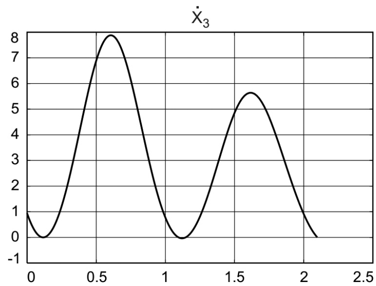

Fig. 4. The $\dot{x}_3$ function for $a = 1$ and $\gamma = 0.7$

Of the numerous results obtained for different values of damping and rough parameters, the solution for the case of large damping with $a = 5$ and a rough parameter value of $\gamma = 0.7$ are shown as diagrams in Figs. 5 to 8.

The values of objective function $J(x, u, w) = x_3$, time of motion t_f and the information whether the necessary conditions for optimisation are fulfilled are all set in Table 1 for the selected tasks with damping taking the value $a = 1$.

Table 1. Objective function x_3 and final time t_f, depending on γ

γ	$J(x, u, w) = x_3$	t_f	**IFAIL**
0.5	5.5169	3.2231	0
0.6	1.5371	2.1847	0
0.7	0.8139	2.0977	0
0.8	3.1888	3.2205	0

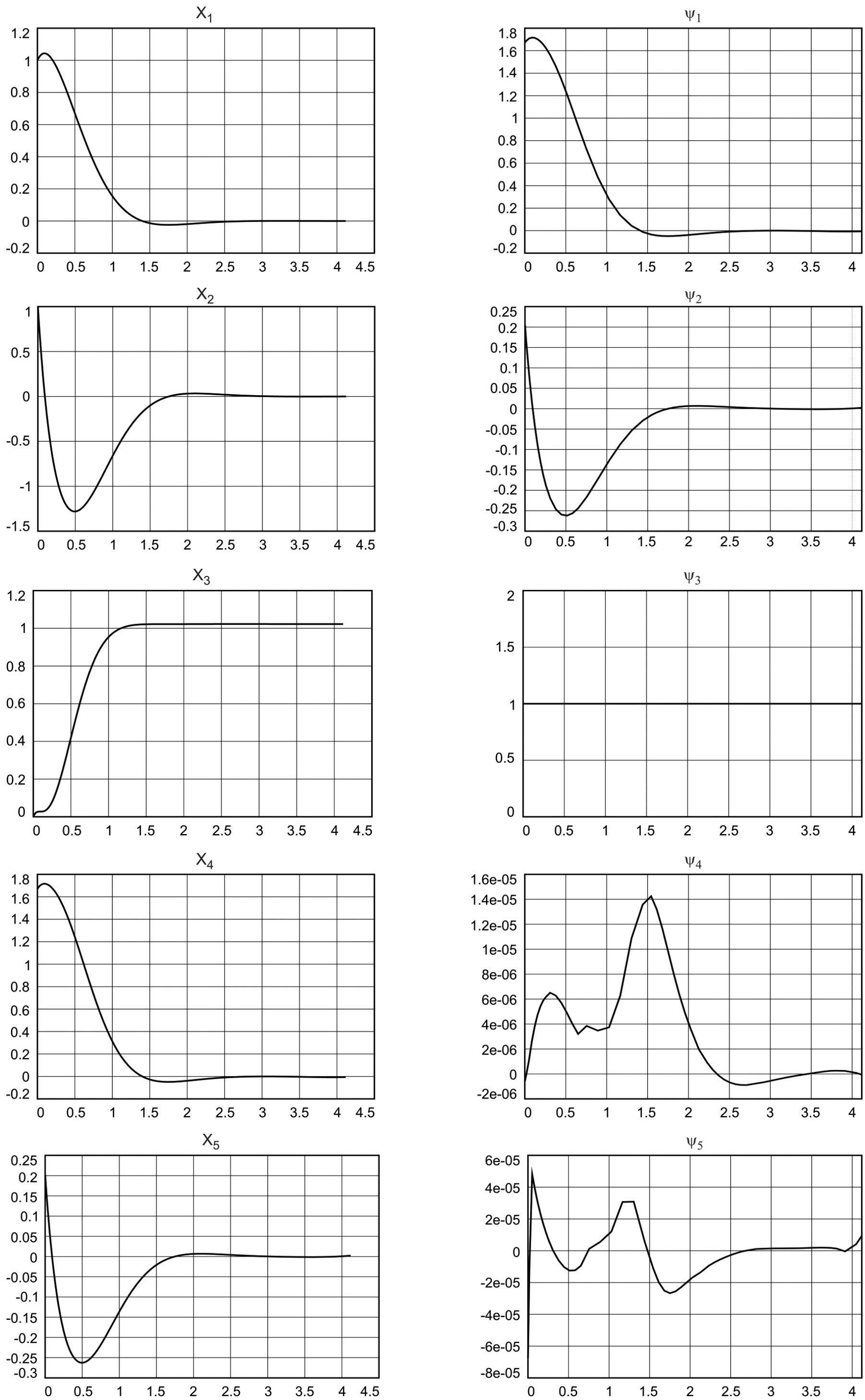

Fig. 5. State variables and corresponding adjoint variables for $a = 5$ and $\gamma = 0.5$

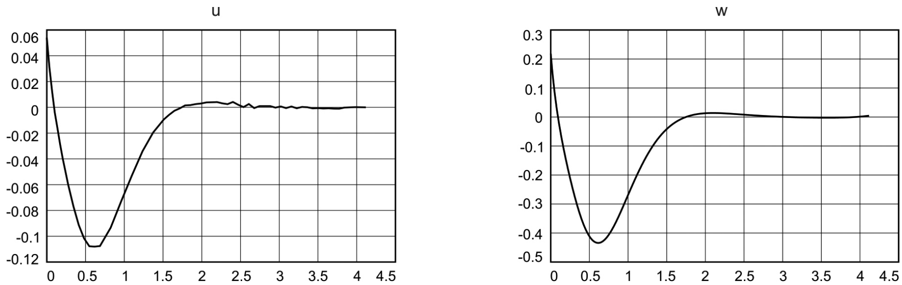

Fig. 6. Control and interference function for $a = 5$ and $\gamma = 0.5$

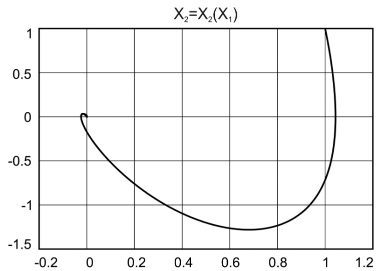

Fig. 7. Diagram X_2 over X_1 in phase-space for $a = 5$ and $\gamma = 0.5$

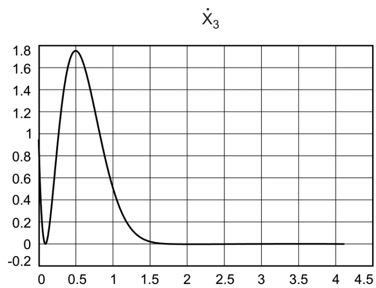

Fig. 8. The $\dot{x}_3$ function for $a = 5$ and $\gamma = 0.5$

6. Summary

The problem of control a nonlinear object, which was the mathematical pendulum, has been discussed in this article. Optimal solutions with regard to the adopted objective function were obtained for the worst interference and for different values of the rough parameter and damping. The boundary value problem resulting from the minimum principle was solved numerically by means of the Dircol software. Complete solutions of the $\min\limits_{u} \max\limits_{w}$ problem have been depicted in the figures. The obtained results, meeting all necessary optimality conditions, confirm that optimal control theory may be effectively used to solve problems of nonlinear object optimisation with the use of a zero-sum differential game.

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Reduction of acoustic cavitation noise emission with textile materials

Redukcja emisji akustycznej szumu kawitacyjnego przy użyciu materiałów tekstylnych

Abstract

This article presents an examination of the acoustic noise level reduction in piping applications. Hydraulic cavitation is the source of the noise. In order to determine the noise level drop for the insulating material arranged around the pipe – cylindrical geometry – the acoustic spectrum was measured in the range of audible frequencies. Measurements were made for textile materials stacked with varying amounts of layers around the source of noise. There was a decrease in the noise level characteristics for mass law. An empirical formula describing the relative noise reduction for the materials under study was proposed.

Keywords: cavitation noise, acoustic insulation, noise emission reduction

Streszczenie

Niniejszy artykuł przedstawia badania redukcji poziomu dźwięku poprzez zastosowanie materiałów tekstylnych wokół rurociągów. Źródłem hałasu jest szum kawitacyjny. W celu wyznaczenia spadku poziomu hałasu dla materiału izolacyjnego ułożonego wokół rury – geometria cylindryczna – zmierzono spektrum widma akustycznego w zakresie słyszalnym przez człowieka. Pomiary przeprowadzono dla materiałów tekstylnych ułożonych z różną ilością warstw wokół źródła szumów. Zaobserwowano spadek poziomu szumów charakterystyczny dla prawa masy. W ramach opracowania wyników wyznaczono wzór empiryczny opisujący względną redukcję poziomu szumów dla badanych materiałów.

Słowa kluczowe: szum kawitacyjny, izolacja akustyczna, redukcja emisji szumów

1. Introduction

Pipelines in industrial and domestic applications can vary from simple, straight structures to often very complex domains. With increasing level of complexity, flow type changes from laminar to turbulent. In specific conditions, turbulent flow may evolve into cavitation. Due to unstable conditions of liquid pressure inside pipes with rapid periodic fluctuations, vibrations of pipeline may occur [9]. These vibrations are transmitted into the air, where they can be measured or, even heard.

This paper presents experimental studies of cavitation noise, its spectrum, specific conditions and method of reduction without affecting on flow conditions. Similar publications can be found where authors describe flow noise emitted from pipes during turbulent conditions and pressure fluctuations [10–17]. More acoustical measurements are performed in publications [18–20], where cavitation noise is considered.

The main idea of this article is to show how to reduce cavitation noise emission in hearing frequencies. As was stated before, crucial conditions to be fulfilled in this experiment, are to prevent even the slightest change in flow conditions. Due to this fact, reduction of noise emission is done by application of sound insulating membrane at the pipe's outer surface. Different material types and thicknesses are considered.

This paper can be applied in design of high velocity flow pipes with liquid, where cavitation may occur, due to extreme conditions of flow and complexity of its means of transportation.

2. Cavitation phenomenon

Cavitation is a phenomenon caused by a variable pressure field in the liquid. This includes the formation, growth and collapse of bubbles or other closed cavities containing a vapour of a given liquid, gas or vapour-gas mixture. Cavitation breaks the continuity of the liquid, thereby increasing the energy loss during the flow. In hydraulic systems, cavitation occurs in pressure areas below the equilibrium vapour pressure of the liquid. As a result of the pressure drop, bubbles form in liquid and flow to the higher pressure areas (above the vapour pressure). In the higher pressure areas, bubbles (cavities) implode causing short-duration acoustic pulses. In the case of developed cavitation (large areas of reduced pressure), the noise of imploding bubbles is so significant that it causes vibrations in the hydraulic systems and--after some time--fatigue of the material [2]. In industrial processes, the phenomenon of cavitation occurs frequently especially in hydraulic systems with high flow rates (large Reynolds numbers). In the recent years, many authors describe cavitation in various components of the hydraulic systems, such as pumps [1], pipelines [7], tees [8], valves [2], Venturi [6], nozzles [5].

A flow with cavitation phenomenon should be treated as a two-phase flow. The beginning of this kind of flow (cavitation occurrence) is defined in the literature using the so-called Cavitation Number *Ca*. According to [6] this number is referred to the ratio:

$$Ca = \frac{P_2 - P_v}{\Delta P} \tag{1}$$

where:

P_2 – static pressure measures after cavitation-causing element;
P_v – equilibrium vapour pressure of the liquid;
ΔP – pressure drop on the obstacle.

Other authors [3] use a relationship determining the cavitation number using kinetic energy of flow:

$$Ca = \frac{P_1 - P_v}{\frac{1}{2}\rho v^2} \tag{2}$$

where:

P_1 – static pressure measures before element causing cavitation;
ρ – density of the liquid;
v – mean velocity measured before the obstacle.

In this paper, authors will be using relationship (2).

With the increase of flow rate, after exceeding a certain cavitation number (critical Ca_{cr}), there is a certainty that cavitation occurs.

The negative effect of cavitation is the noise generated by the imploding vapour bubbles of the liquid, which are moving from the reduced pressure area to the higher pressure area.

Experimental and theoretical studies show that there is a difference in the mechanism of cavitation noise formation in gas and vapour bubbles [9]. For gas bubbles, acoustic waves are generated by bubble oscillation.

3. Test setup

Measurements were performed using the setup shown in Fig. 1. The cavitation phenomenon was induced in the Venturi shown in Fig. 2. During the test, measurements of flow rate, the pressure drop on the orifice and the pressure on the orifice relative to the ambient (atmospheric) pressure were made. In the test setup, water was the liquid in which cavitation occurs. Based on the results for different flow rates, the cavitation number for each case was determined and set the critical cavitation number indicating the initialization of cavitation (Fig. 3).

In the test setup Wilo MHI 202 pump, the Fuji Electric Portaflow X flowmeter and the Peltron PXWD pressure difference sensors were used. The measurements of acoustic noise were performed for the parameters indicated by triangles on Fig. 3.

In acoustic measurements, 01 dB Metravib Blue Solo SLM (Sound Level Meter) was used. The level meter was set in a 17.5 cm distance from the longitudinal axis of Venturi orifice in order to provide free field conditions from 500 Hz J. Cowan, Building Acoustics, in: Springer Handbook of Acoustics, red. T.D. Rossing, Springer Science, Leipzig 2007, pp 387–425, 390. Noise measurements are set up to the frequency of 25.6 kHz. Analysis of noise level drop was performed up to 1/3 octave band of 20kHz. Two factors are responsible for it. The first one is the reduction of tests to the upper hearing frequency. The second one is the technical limit of SLM used in tests, which provides the highest sample rate at the level of 51.2 kHz. It directly results in Nyquist frequency of 25.6 kHz, which is followed by the fact that only below this frequency, can measurements be done. The full spectrum of cavitation measurement is shown on Fig. 6.

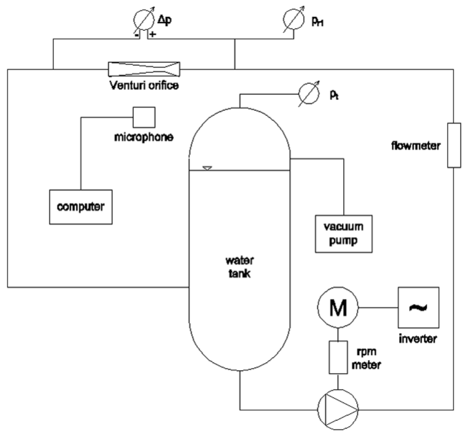

Fig. 1. Test setup

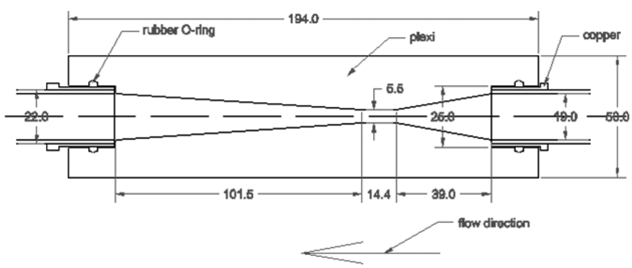

Fig. 2. Venturi orifice

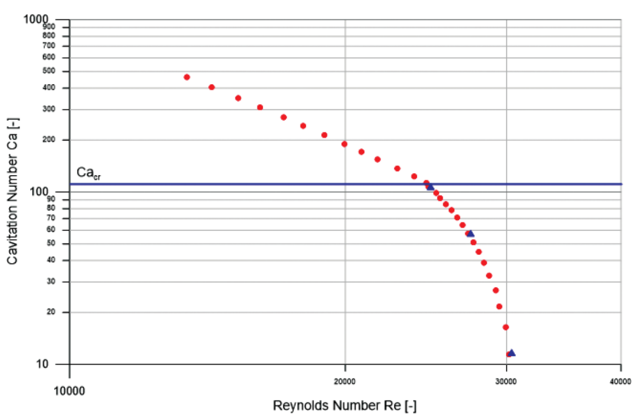

Fig. 3. Cavitation number for different flows using test setup

In order to measure the insulation of pipe covering, Venturi orifice and adjacent elements were lagged with different textiles of varying thickness. Measurements were performed for the given set of coverings:

- textile type 1: 2 layers, 4 layers, 8 layers,
- textile type 2, 4 layers, 8 layers, 16 layers.

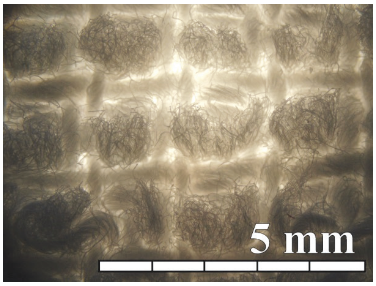

Fig. 4. Insulation textile material type 1

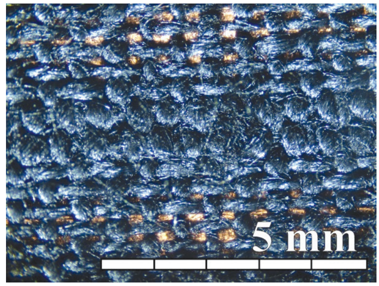

Fig. 5. Insulation textile material type 2

4. Results of measurements

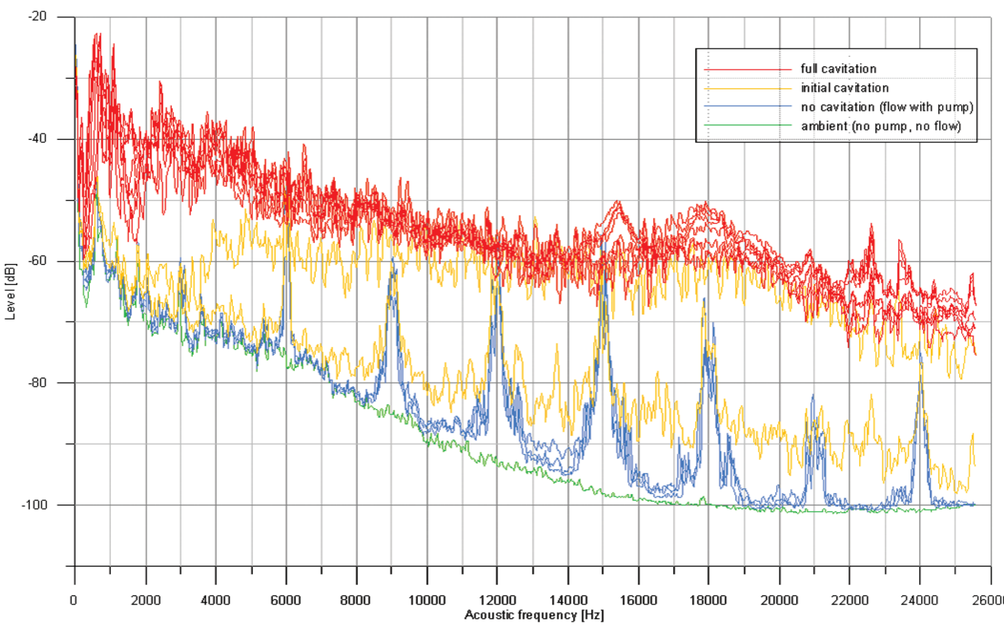

Fig. 6. Spectrum of cavitation noise for different Re number without insulation

5. Results of modified setup measurements

After insulating the Venturi, measurements were conducted in conditions given below in Table 1 and Table 2.

Table 1. Measurement conditions

Pump current frequency [Hz]	Pump [rpm]	Re [–]	Ca [–]
27.9	1612.6	24783	107.6
35.0	2016.1	27411	57.6
43.0	2463.9	30376	11.7

Table 2. Area density of used materials, per one layer

Material	Mass of sample [g]	Area [cm^2]	Area density [kg/m^2]
type 1 (open porosity)	366.22	9380	0.39043
type 2 (open porosity)	516.85	17238	0.29983

The analysis of insulation measurements of chosen textile materials is given below on Fig. 7. The lowest 1/3 octave band is 6.3 kHz due to the fact that below this band there were no transmission losses of cavitation noise. The difference between measured noise and background and pump noise was above 10 dB in each band above 400 Hz.

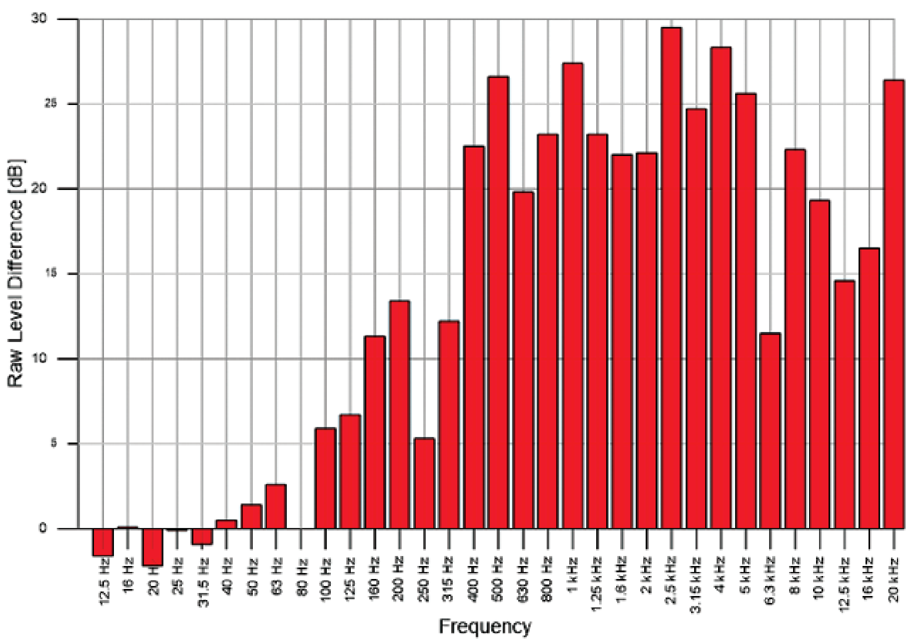

Fig. 7. Raw level difference between average cavitation noise and average background/pump noise

Due to the fact that there were significant instabilities in measurement results with pump current frequency of 27.9 Hz, it was decided to remove these results from the final analysis. It was an initial stadium of cavitation. Additionally, there was a lack of repeatability for textile type 2 with 2 layers mounted, so these measurements were also rejected in further analysis.

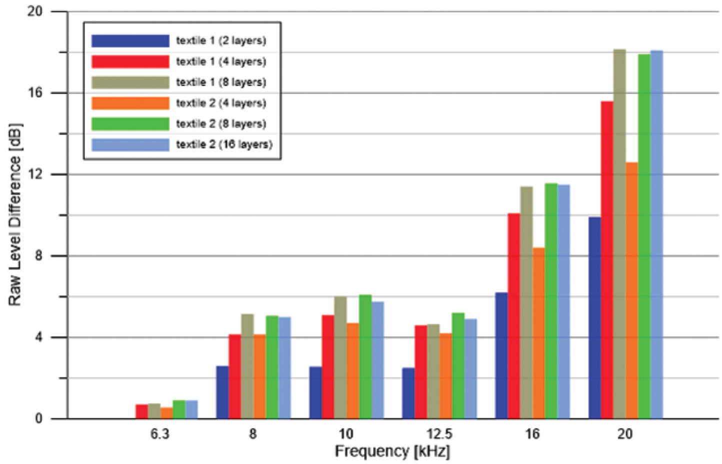

Fig. 8. Measured raw level difference between setup with and without insulation

6. Discussion

As an analogy to measurements of sound insulations of building partitions in standard ISO 16283-1:2014 [23] omnidirectional sound source is replaced by Venturi orifice with cavitation phenomenon inside. Cavitation noise level is sufficient to test level differences occurring in tested materials.

For textile materials tested in this paper, the level difference is found at 8 kHz. In both materials there is a drop in 12.5 kHz. It is probably caused by local resonances of the measuring system. The influence of pump/background noise was excluded. In case of noise level difference generated by pipe covering, the total level values as dBA or dBlin are below 2 dB, which is a prerequisite to reject this method of evaluation,even though noise level reduction is measured. This is caused by the fact, that dBA or dBlin takes into account the whole audible spectrum. In the measured case, only frequencies above 8kHz are evaluated.

In order to describe measured noise level reduction caused by textile pipe covering, the following formula (3) is proposed:

$$\Delta L\left(f, m'\right) = 10 \cdot \log_{10}\left(f^{3.5} \cdot m'^{0.8}\right) - 136 [\mathrm{dB}] \tag{3}$$

where:

f – frequency band [Hz];

m' – area density of pipe covering [kg/m^2].

Exponents were selected based on best fit and Pearson correlation coefficient squared and showed in Fig. 9.

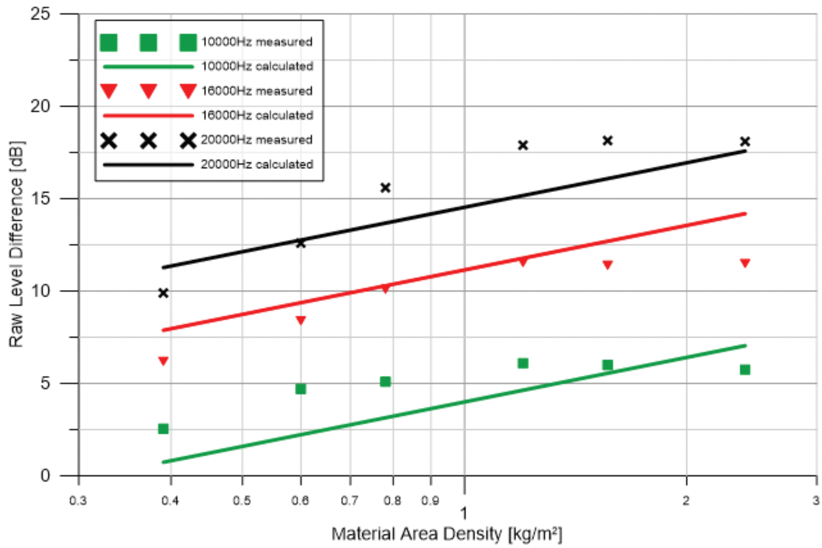

Fig. 9. Comparison between measured raw level difference as function of material area density and calculated values using formula (3)

Table 3. Pearson squared coefficient values for each frequency

Frequency [Hz]	R^2
8000	0.7872
10000	0.7181
12500	0.6264
16000	0.8325
20000	0.8619

The given formula (3), based on measured results, is classified as empirical one. It assumes analogous geometry of pipes. This formula is analogous to mass law for homogenous, flat partitions which can be found in David A. Bies, Colin H. Hansen, Engineering Noise Control: Theory and Practice, Fourth Edition, p.191, 2003.

7. Conclusion

After the performed measurements and calculations, the following conclusions can be drawn about cavitation noise and textile pipe coverings:

- textile multilayer materials with area density between 0.4–2.4 kg/m^2 have the ability to decrease cavitation noise starting from frequency of 8 kHz,

- there is a possibility to find empirical interdependence between noise level reduction, and frequency with area density,
- cavitation as a phenomenon is good for insulation measurement, because cavitation itself generates noise in the full spectrum of audible frequencies.

In further studies, verification of extrapolation of empirical formula on frequencies lower than 8 kHz will be performed. Additionally, samples with higher area density will be tested.

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Adaptation of coutyards into covered and glazed atriums and its impact on the level of acoustic comfort inside – case study

Adaptacja zamkniętych dziedzińców na zadaszone i przeszklone atria oraz jej wpływ na poziom komfortu akustycznego wnętrza –studium przypadku

Abstract

Increasingly popular, in the area of modernization or revitalization of historic buildings, is the creation of a roof that is often fully glazed over the inner courtyard, thus creating a new spacious interior capable of performing many functions. The acoustics evaluation undertaken in this article was carried out on the basis of measurements and simulation of reverberation time in The Home Army Museum building in Cracow.

Keywords: architecture, atrium, acoustics; architectural acoustics; room acoustics

Streszczenie

Coraz popularniejsze staje się w ramach rewitalizacji zabytkowych obiektów wykonanie zadaszenia nad dziedzińcem wewnętrznym i stworzenia tym samym nowego przestronnego wnętrza mogącego pełnić bogate funkcje. Podjęta w artykule ocena akustyki wnętrza została wykonana na podstawie pomiarów i symulacji czasu pogłosu w budynku Muzeum Armii Krajowej w Krakowie

Słowa kluczowe: architektura, atrium, akustyka, akustyka wnętrz

Symbols

T_{20}, T_{60}, RT – reverberation time [s],
T_{pref} – preferred reverberation time [s],
V – room interior volume [m^3],
A – total acoustic absorption of the room,
S – overall interior surface area [m^2],
α_{sr} – average sound absorption coefficient.

1. Introduction

Courtyards in historical buildings usually have a significant utilitarian and representative role; its form and dimensions often represent the social and material status of the owner. It could be a place for meetings, celebrations, or a space used for rest. Nowadays, the role of the courtyard has not changed significantly, but the current user expectations and requirements have indicated the need to revise the arrangement of these spaces. Increasingly popular, in the area of modernization or revitalization of historic buildings, is the creation of a roof that is often fully glazed over the inner courtyard, thus creating a new spacious interior capable of performing many functions. Primary contact with nature and the outside environment is preserved, as is the plasticity of the resulting structure. It also enhances visual experiences, which are not limited by the layers of the roof [1].

A new design allows one to use such a room in many new ways. It creates space for exhibitions, chamber concerts, lectures, film screenings, art exhibitions, installations and sculptures whose form and scale would not allow exposure in traditional spaces. These solutions bring many benefits, extend the functionality of the building, and increase both the usable area and the value of the object itself [2], but present the designer with a number of challenges that must be overcome at the concept stage. During the design phase of such an adaptation, the architect most often focuses on creating the best form, function, and construction of the whole object without delving into time-consuming analyses of how their decision will affect the acoustic comfort of the interior. This is not due to a lack of willingness but to a shortage of suitable design tools that could improve the design process in the context of acoustics.

Finishing the interior exclusively with hard and smooth materials, without the use of sound absorbing materials, increases the noise level and prolongs the reverberation time. People in such interiors will have difficulties communicating with each other which can lead to the Lombard's effect: the tendency of the interlocutors to gradually increase the intensity of their voices when the conversation takes place in loud environments. Reverberation time is the basic parameter for acoustic evaluation of interiors and, in order to reduce it, the best solution is to use tested interior sound absorbing materials. Acoustical performance of atriums cannot be expected to be on par with lecture rooms or concert halls, but attention should be paid to the application and even distribution of sound absorption in the existing interior [3]. Assessment of interior acoustics in this article was made on the basis of measurements and simulations of reverberation time (T_{20}).

2. Description of the case study

The courtyard selected for the assessment of the interior acoustic comfort is located in The Home Army Museum in Cracow. (Fig. 1). The building was formerly a military facility and was part of a unique architectural complex of the former Cracow fortress. In 2011, the revitalization of the facility was completed. The exterior of the building did not change, as the renovation work was focused on preserving the original character of the building [4].

a)

b)

Fig. 1. a) The Home Army Museum front elevation (source: [11]); b) Interior of the atrium (source: [12])

External facades have been cleaned, windows have been replaced and the roof sheathing has been covered with ceramic tiles. The biggest changes took place in the interior. The facades of the courtyard were rebuilt with a glass roof made over them. The newly built room not only became an impressive exhibition area, but also "the heart" of the whole building. The atrium, apart from the communication and exhibition function, is also a place where various types of productions, lectures, and even concerts are organized. (Fig. 2).

The dimensions of the hall are approximately 15 x 27 m, and the height of the roof varies between 9–12 m. The atrium's volume is approximately V = 4 455 m^3 with a total area of interior surfaces at around S = 1 735 m^2. The main materials used for interior finishes are ceramic bricks, plaster, steel, wood and glass (Fig. 2).

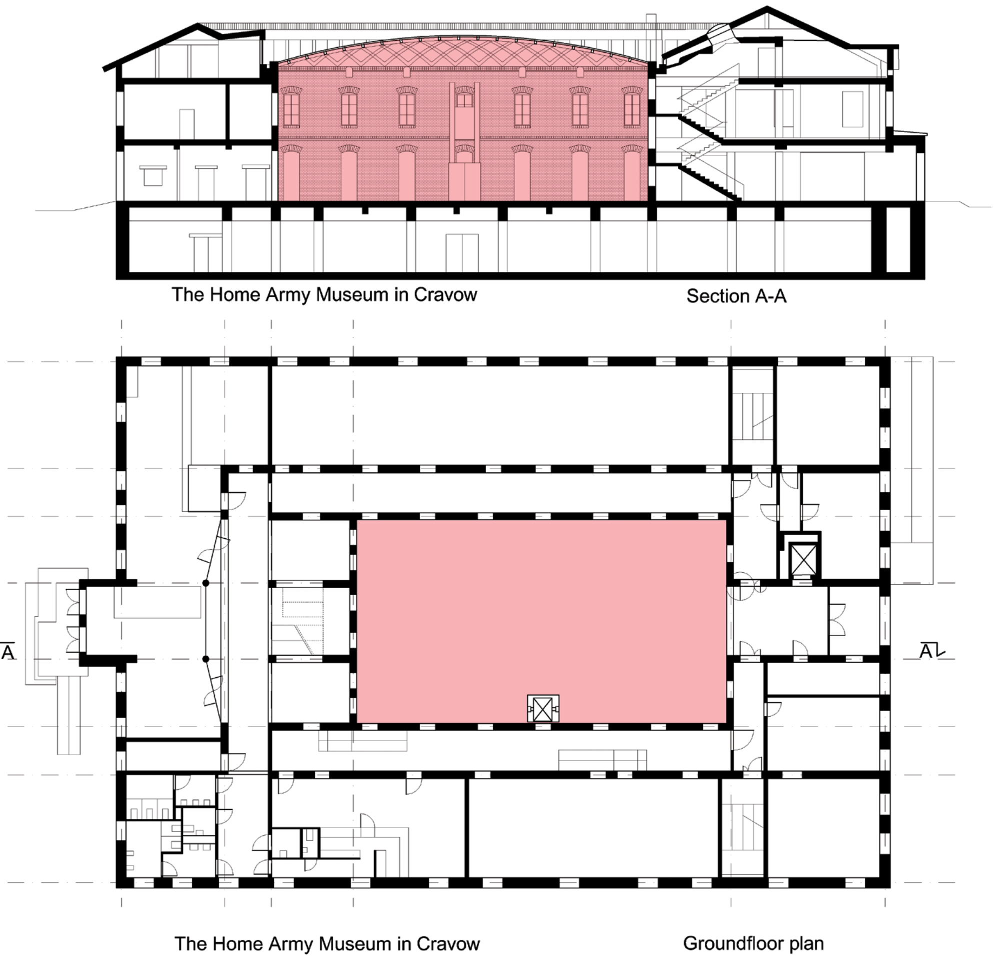

Fig. 2. Plan and cross-section of The Home Army Museum in Cracow with the location of the atrium (source: ?? ??)

3. Measurements

Measurements were made using Class 1 sound level meters. Reverberation time measurement was performed using an omnidirectional pulse signal (balloons shots). Impulse response to noise ratio (INR) reached values from 38 to 60, and they are accurate for measurements of T20. Reverberation time measurements have been carried out in accordance with PN-EN ISO 3382-2: 2009 [5]. During measurements, the room was empty except for a small artistic installation in the central part. The reverberation time was determined by a Bruel & Kjaer software – DIRAC.

4. Results

Measurements have shown that the Reverberation Time (T_{20} s) in the examined condition of the interior finish is about **3.53 s** at 1000 Hz and rises in lover frequencies to about **6.14 s**. Full results of the reverberation time (T_{20}) are shown in Table 1 and Fig. 4. In order to illustrate and better understand the effect of roofing, the reverberation time also shows the T_{60} results for a courtyard without a roof above. Reverberation time in second variant is about **1.24 s** at 1000 Hz and increases to a value of **1.49 s** in the lower frequencies. Values for the courtyard without a roof have been calculated with the Sabine formula (1) [6]:

$$T60 = \frac{0.161 * V}{A} = \frac{0.161 * V}{S * -sr} \tag{1}$$

where:

- T_{60} – reverberation time (s),
- V – room interior volume (m^3),
- A – total acoustic absorption of the room,
- S – overall surface area (m^2),
- α_{sr} – average sound absorption coefficient.

Preferred Reverberation Time values for a room with the given volume and height are according to PN-B-02151-4:2015-06 [7] $\boldsymbol{T_{pref}} \leq$ **2.0 s** (exhibition halls in museums and other rooms with similar purposes).

Table 1. Measured and simulated values of reverberation time according to PN-B-02151-4:2015-06

Frequency	125 Hz	250 Hz	500 HZ	1000 HZ	2000 Hz	4000 Hz
Courtyard with roof – measurements in situ	6.14	5.72	4.02	3.53	2.64	2.22
Courtyard without roof – theoretical calculations	1.49	1.45	1.34	1.24	1.12	1.08
Acoustic requirements PN-B-02151-4:2015-06	2.00	2.00	2.00	2.00	2.00	2.00

The main requirements contained in the Regulation of the Minister of Infrastructure from 12 April 2002 on the technical conditions to be met by buildings and their location refer to:

- protecting spaces against reverberation noise arising as a result of reflections sound waves by partitions limiting the room,
- ensuring proper speech intelligibility in verbal communication facilities [8].

Noise reverberation depends on the volume of the room and the materials from which the partitions are made. Noise reverberation will be greater in high volume rooms and in interiors where hard materials are used. To reduce the occurrence of reverberation noise, the volume of the projected room should be reduced, or materials with sound absorbing properties should be used. STI is an object-oriented quantification of speech intelligibility in a room and primarily depends on the background sound level, reverberation time, and distance from the source of the signal [9].

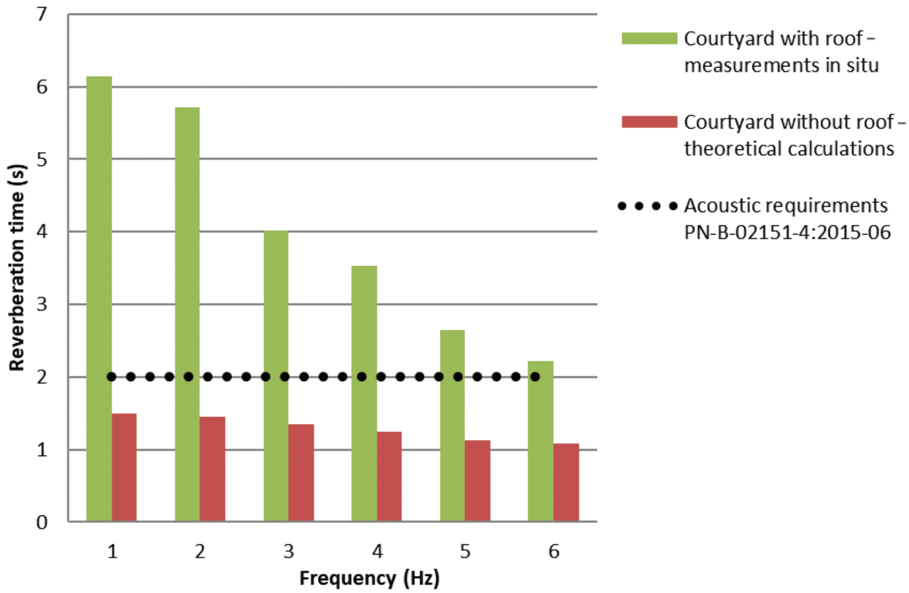

Fig. 3. Measured (T_{20}) and simulated values (Sabine) of reverberation time (source: ?? ??)

The Polish standard PN-B-02151-4: 2015-06 presents specific requirements pertaining to the reverberation time or speech transmission index (STI) for selected groups of unqualified rooms. It can be assumed that when the requirements of the Polish standard are fulfilled, the Technical Conditions of the acoustics can also be considered as fulfilled.

Requirements for atriums, halls and foyers are different from the requirements intended for exhibition halls and gallery exhibitions in museums. For the first group of rooms, depending on their height, the maximum reverberation time is between 1.2 s–1.8 s. The requirements for exhibition halls and showrooms in the Table 1 are more lenient and are between 1.8 s and 2.5 s.

For the atrium of the Home Army Museum in Cracow, the maximum preferred reverberation time was $T_{Pref} \leq 2$s. However, the results of the measurements show that the roofing in the courtyard dramatically increases the RT, which clearly exceeds the permissible normative values. Large volume and lack of furniture, while using hard surfaces, reduces the reverberation time needed for proper verbal and indirect communication, as well as, reception of multimedia installations. Since it is not possible to change the dimensions of the room, the only solution is the use of sound-absorbing materials in the interior. The amount of sound-absorbing material should be determined on the basis of calculations and should be distributed over each of the three pairs of parallel surfaces. The type of sound-absorbing material, its area and the mounting location will have a decisive impact on the fulfillment of standard requirements, and its uniform distribution will avoid flutter echoes. Usage of sound-absorbing material in this case, for example in the form of a suspended membrane under roofing, will be insufficient and it is advisable to place sound-absorbing material on at least one of the opposite walls [10]. Rounded roofing with no sound absorbing materials on the opposite walls makes the flutter echo effect of a clearly audible in the center of the room (Fig. 4).

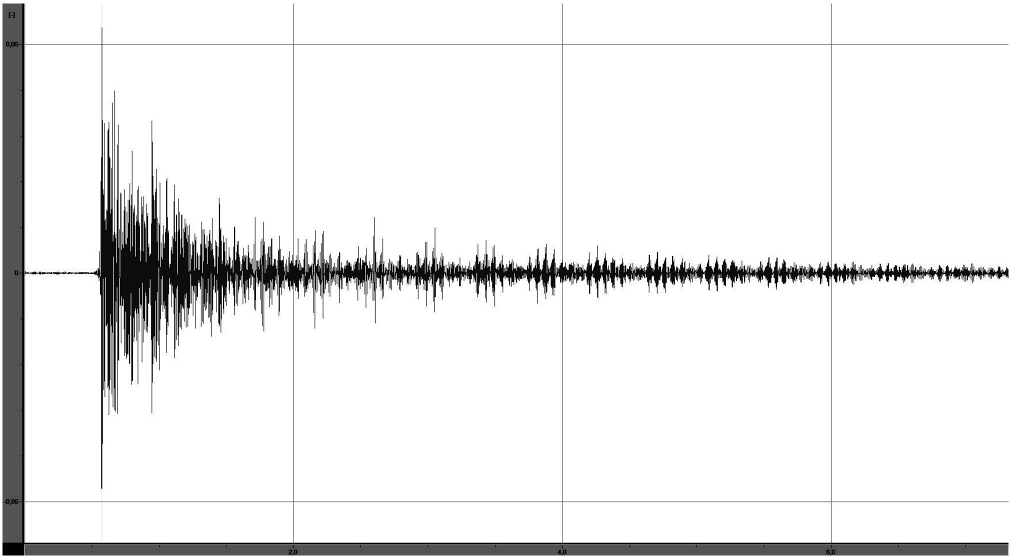

Fig. 4. Measured flutter echo in the atrium

5. Conclusions

Placing glazed roof over an existing courtyard brings a significant changes in the way one uses the space, forcing the architect to make important decisions at the concept stage so that the interior conditions are favorable for the future user. In addition to the obvious structural features of additional roofing, the designer should also analyze how the interior acoustics will change and how it will affect the comfort of use. Design work cannot be entirely dependent on acoustic considerations, but taking them into account early in the project can reduce the costs of adapting the premises to achieve the desired acoustic comfort.

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The quality of coal in Poland, Russia and Ukraine and its effect on dust emission into the atmosphere during combustion

Jakość węgla kamiennego w Polsce, Rosji i na Ukrainie oraz jej wpływ na emisję pyłów do atmosfery podczas spalania

Abstract

This paper presents the characteristics of coal quality in Poland as well in Ukraine and Russia – the two largest import sources. The analysis was carried out on the energy coal market for domestic use in all three countries from the perspective of the supply, demand and current prices. Thereupon was the analysis of the potential dust emission during combustion that results from the natural ash content in the coal, and with consideration to the efficiency of the furnace and the combustion method. The results of the analysis and the computation show that there are no significant differences in the quality of the coal from Poland, Ukraine or Russia. However, the important factor is the calorific value and, closely related to it, the content of non-combustible solids and dust emission. The analysis of dust emission proves that the impact on the environment can be significantly reduced by burning coals with a minimum calorific value of 27,000 kJ/kg.

Keywords: coal quality parameters, steam coal market, coal combustion, dust emission

Streszczenie

W artykule przedstawiono charakterystyki jakościowe węgla kamiennego występującego i wydobywanego w Polsce oraz na Ukrainie i w Rosji – dwóch najbliższych źródeł jego importu. Przeprowadzono analizę rynku węgla energetycznego ww. krajach pod kątem celów komunalno-bytowych, analizując jego dostępność, zapotrzebowanie oraz aktualne ceny. Następnie wykonano analizę potencjalnej emisji pyłu węglowego wynikającego z naturalnej zawartości popiołu w spalanym węglu, uwzględniając możliwą sprawność kotła i metodę spalania. Wyniki analiz i obliczeń pokazują, że nie ma istotnych różnic jakościowych pomiędzy węglem polskim, ukraińskim i rosyjskim. Istotnym szczegółem jest jednak jego kaloryczność, która ściśle przekłada się na zawartość w nim cząstek stałych i emisję pyłu do atmosfery. Wpływ spalania węgla na środowisko naturalne będzie ograniczony, gdy będą spalane węgle o wartości opałowej minimum 27 000 kJ/kg.

Słowa kluczowe: parametry jakościowe węgla, rynek węgla energetycznego, spalanie węgla, emisja pyłu

1. Introduction

The European Union environmental policy is focused on reducing the share of solid fuels (hard coal and lignite) in energy production in the EU. This process is expected to lower the content of particulate matter (PM) in the air (dust PM 2.5 and PM 10), and lower the emission of carbon monoxide and carbon dioxide, especially in mining areas. Parallel to the reduction in the use of hard coal and lignite for electricity and thermal energy production, the quality requirements for solid fuels are becoming increasingly stringent. This situation imposes a need for a new methodology for the evaluation of coal resources the on mining industry – an evaluation not limited to technical and economic aspects of exploitation but broadened to cover coal quality and its impact on the environment during combustion.

The forecasts of experts indicate that coal will continue to be the basic source of energy in Poland in the next few years, and the main energy security factor. The share of hard coal in energy production in the year 2050 is estimated to be as much as 9-45 million tons, depending on the development of nuclear power, clean coal energy technology, changes of other fuels prices and prices for CO_2 emission permits [4].

According to recent changes in the law regarding the environmental protection local governments have the right to decide which fuels are permitted and which are banned, as well as to set the emission standards for furnaces in their areas [10]. In effect, certain low-quality fuels like coal sludge or coal flotation concentrate may be banned in the city or rural communities, as well as furnaces which do not comply with environment protection standards.

The changes in the law were intended to improve the quality of the air in the cities and rural areas of the highest air pollution; among these are areas of deep coal mining. On the basis of the law, anti-smog acts have thus far been introduced in, for example, Małopolskie and Silesia voivodships. The act in the Silesia voivodship can be assumed to be a model regulation for setting the emission limits for heaters, furnaces and fireplaces, as well as procedures for their replacement. This act prohibits also the use of lignite, coal sludge, flotation concentrate and wet wood – this commenced on 1st September 2017. Comparing this regulation with the anti-smog law in the Małopolskie voivodship, where coal and wood burning is entirely banned, the Silesian model better compromises the imperative of environment protection and the expectations of society.

The use of highly calorific and low ash content coals could be an effective solution to the problem. However, this solution necessitates suitable fuel sources. Import of coal may be needed if it is not produced locally up to the required quality and quantity. Russia and Ukraine are the largest producers and potential exporters of hard coal in Europe. The question arises of whether the Russian and Ukrainian coals can compete with coal from Poland in terms of quality and price.

As a result of the above question, the objective of the research presented in this paper was an analysis of the basic quality parameters of hard coals and subsequently providing a comparison which considers the different quality and economic criteria of coal supply from all three countries. A brief analysis was also carried out of the dust emission and environmental impact of coals of various calorific value and ash content burnt in household furnaces of different combustion methods and efficiency levels.

2. Deposits and parameters of coal in Poland

2.1. Deposits

In the national inventory of hard coal resources at the end of 2015 [23], there was a total of 156 coal deposits, including 51 developed deposits, 47 abandoned, and 58 which were documented but yet not developed. Of the last group, the resources of 18 deposits were documented in the initial C_2+D category while 40 deposits were documented in detailed category A + B + C_1 (35 – in the Upper Silesia Coal Basin *GZW*, 4 – in the Lublin Coal Basin *LZW*, and 1 in the Lower Silesia Coal Basin *DZW*).

In total, according to the balance of 31.12.2015, the economic resources within the undeveloped deposits were recorded as 31.20 billion tons comprising 20.21 billion tons in *GZW*, 10.39 billion tons in *LZW*, and 600 million in *DZW* [23].

According to the same national reserves inventory on 31.12.2015, the total economic reserves of hard coal were 56.22 billion tons, including 21.11 billion tons in deposits currently being exploited. The recoverable resources were estimated at 3.56 billion tons, which is comprised of 3.30 billion tons in the exploited deposits and 251 million tons in the mines under construction [23].

Energy coal types 31–33 (steam coals) constitute the largest part of the recoverable reserves [22], and amount to 53.4% of the total recoverable resources and 58.4% of the developed resources (Fig. 1). Of the entire energy production in Poland, 86% is from solid fuels and almost 50% is from hard coal. The remaining 36% is from coking coal (type 34) and ortho-coking coal (type 35). The other coal types (36–38) constitute around 1% of the developed resources.

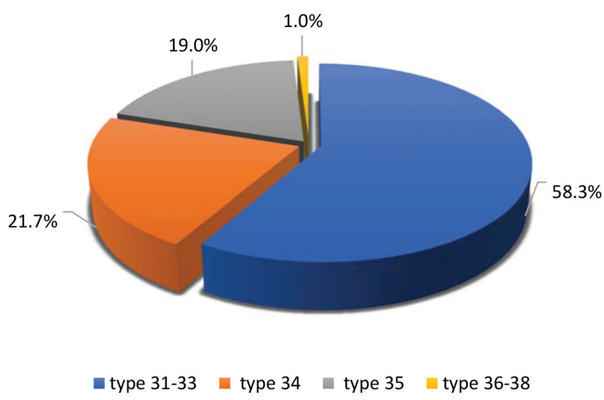

Fig. 1. Distribution of hard coal types in recoverable resources of coal in Poland

2.2. Quality parameters of coal

The quality parameters of coal (calorific value and ash and sulphur content) in recoverable reserves are the main factors considered in the design of the mine (deposit) development. These factors have the strongest effect on the economic effectiveness of the mine determined by the coal price formula [9]. From an energy production point of view, the calorific value parameter is crucial. The developed mines hold recoverable reserves of high calorific value coals. More than 92% of the reserves are in levels that are either already developed or are being developed show calorific values higher than 22,000 kJ/kg (Fig. 2), compared to the 15,000 kJ/kg criterion for the category of economic reserves [22].

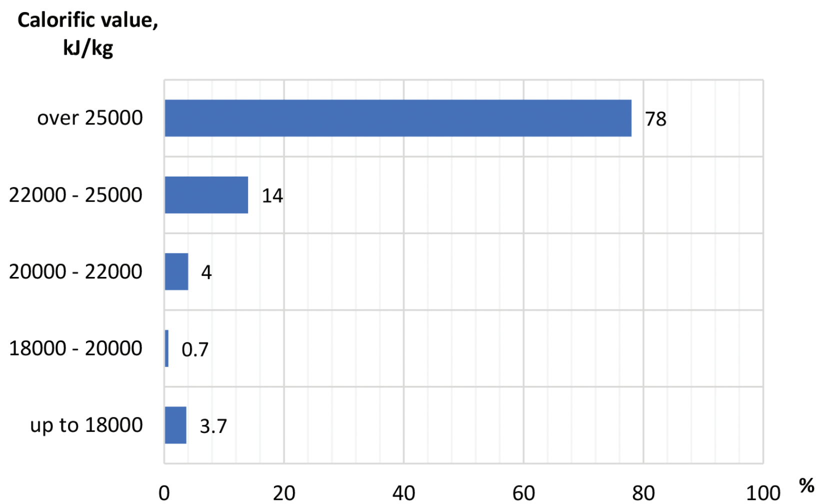

Fig. 2. Distribution of hard coal resources in Poland vs. calorific value

Another quality parameter (ash content) is closely related to calorific value. The lower this index, the higher the calorific value of hard coal. The majority of the resources (81.2%) show an ash content of below 15% (Fig. 3). More than half of the total recoverable resources fall into the low ash category defined as containing less than 10% of non-combustible matter. This amounts to 3.01 billion tons, of which number 2.15 billion tons is in developed levels, or levels that are being developed. The percentage of coals with an ash content higher than 20% in the total recoverable reserves is steadily decreasing. According to the inventory of 01.01.2015, this kind of resource constituted 5.5% of the total recoverable resources [22].

As a result of the above figures, it can be concluded that the hard coal reserve in Poland is ample and the coal is generally of a high calorific value and low ash content. However, the natural ash content in coal – a contamination created during coalbed formation processes, may not be representative of the ash content of the excavated bulk material. The excavated coal may show a higher ash content due to the presence of waste rock intercalations in the coal bed (mainly mudstone); especially if it is more than 5 cm thick. Moreover, excavation of coal beds of a thickness less than 1.5 m, due to the technology of excavation, imposes over-excavation into the roof or floor of the bed, hence the addition of waste rock to the coal that needs to be separated later through processing. Unfortunately, practice shows that the separation process is not fully effective and that in these circumstances, the ash content significantly increases.

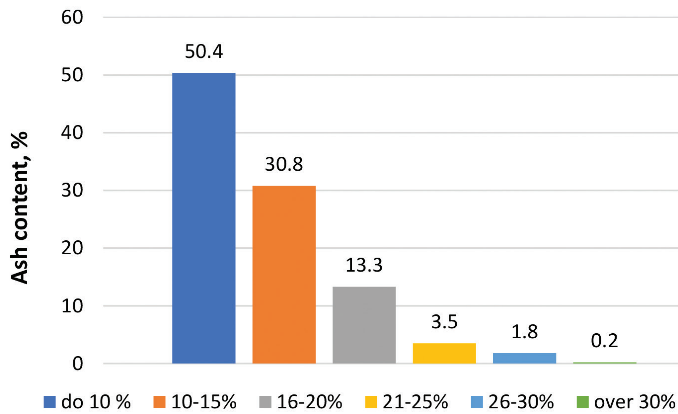

Fig. 3. Distribution of hard coal resources in Poland vs. ash content

Figure 4 displays the distribution of recoverable hard coal reserves versus the coal bed thickness. Its analysis shows up to 20% share of coal resources in beds thinner than 1.5 m, hence in a situation where the ash content in coal will increase due to the technology of excavation [22]. Even though this share has halved (from 39.9%) since year 1991 it is still significant, especially considering that the production of coal has also nearly halved since then. Between 2003 and 2013, the average content of waste rock in coal has increased from 26% to 31.5% [5]; therefore, by applying a trend line, it may reach 32.5–33.0% today, i.e. one third of the output. The case of certain mines shows the content of waste rock in daily excavation to be up to 45–48%. The analysis of the share of thin coal beds in the resources planned for development (Fig. 4) allows us to anticipate that it will remain generally unchanged over the next few years.

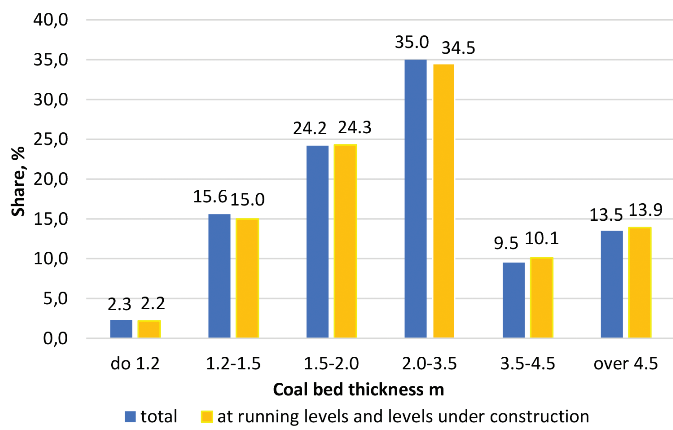

Fig. 4. Distribution of hard coal resources in Poland vs. thickness of beds

Sulphur appears in the hard coal in three forms: as organic compounds, pyrites (FeS_2) and sulphates. Sulphur dioxide (SO_2) – a gaseous product of hard coal combustion – is one of the major pollutants of the environment. Reduction of the high emission of sulphur dioxide is the priority of the European Union environmental protection policy.

Sulphur is found in coal beds at a wide range of levels from traces up to over twelve per cent. However, the average content of sulphur in the hard coals of GZW is low and amounts to about 1.2%, whereas the range of sulphur content is 0.32–2.82%. Most frequently, the sulphur content does not exceed 0.6% [22] (Fig. 5).

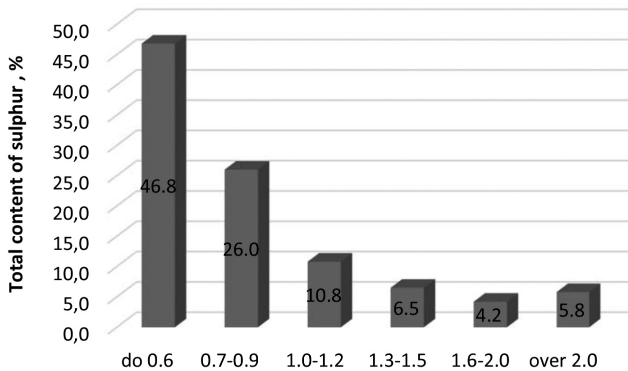

Fig. 5. Distribution of hard coal resources in Poland vs. total sulphur content

3. Deposits and parameters of coal in Ukraine

The recoverable resources in Ukraine, at depths of up to 1,500 m deep, are estimated to be 117.3 billion tons. However, around 80% of these resources are in thin beds (up to 1.2 m) and very thin beds (less than 0.7 m) [2] – Fig. 6.

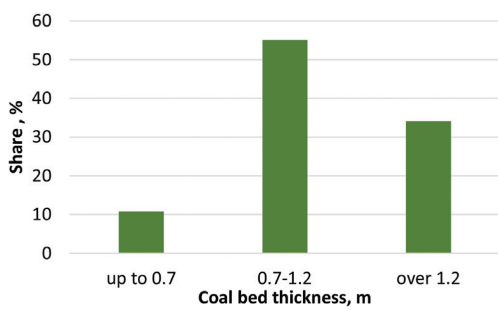

Fig. 6. Distribution of hard coal resources in Ukraine vs. thickness of coal beds

As is the case in Poland, the largest proportion of the recoverable resources in Ukraine are energy (steam) coals of types D, G and GZh, constituting around 60%. The resources of coking coal are estimated to be at around 8% (types K and Zh); 12% – ortho-coking coal (type OC); 20% – anthracite (types A, P) of the total recoverable resources (Fig. 7). Around 40% of energy coal is used for electrical energy production, while around 14% is annually allocated to be used in households.

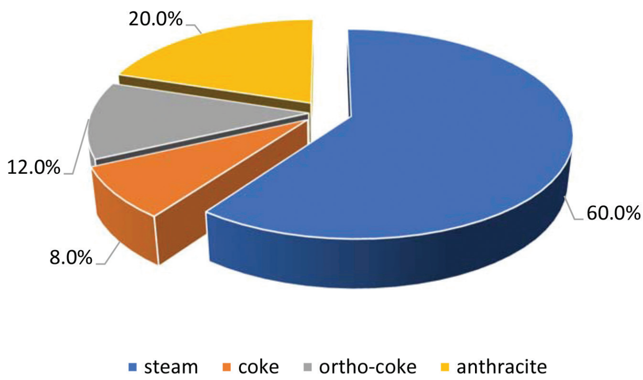

Fig. 7. Distribution of hard coal types in coal resources in Ukraine

The energy coal in Ukraine is characterised by high calorific values of 25,000 kJ/kg and above. However, due to numerous waste rock intercalations in the coal beds and the presence of faults, as well as the applied technology, the coal becomes contaminated and the average calorific value drops to 21,000 kJ/kg or lower.

Coal in Ukraine is also characterised by higher energy coal content of sulphur than in Poland's coal. Within the Ukrainian deposits, the predominant coal categories are sulphur contaminated and highly sulphur contaminated with the sulphur contents of 1.5–5.5% [12]. As a consequence, the coal is subject to intensive processing to achieve energy coal quality criteria, which affects its final price.

4. Deposits and parameters of coal in Russia

To date, around one third of the world's coal resources are geologically documented on Russian Federation territory – this amounts to 193.3 billion tons, of which 101.2 billion tons is hard coal and 85.3 billion tons is lignite [30]. The breakdown of hard coal in the Russia Federation into lithotypes from energy coals to anthracites is presented in Fig. 8. The largest proportion of these resources is found in the Siberia-Kuznieck, Kansk-Aczynsk, Peczorsk, Irkuck and Ulug-Chemsk coal basins, and in the East Donbas-Donieck coal basin. These coal basins are characterised by favourable geological conditions i.e. relatively shallow locations of coal beds (down to 400-500 m, in several cases down to 1000 m), thick coal beds (around 40.6 % of average thickness 1.8–3.5 m, and 38.2 % beds thicker than 3.5 m), and infrequent tectonic disturbances (Fig. 9). Both deep mining and open-pit mining methods are used to develop the coal deposits [3].

The share of hard coal in energy production in 2017 was recorded at 25%. The experts forecast a gradual increase in this value that will reach 35% by the year 2020. This trend is related to the projected demand for electrical energy and the growing export of natural gas to Asian countries. Russian energy coal, like Ukrainian coal, is characterised by calorific value in the range 20,000–25,000 kJ/kg (Fig. 10).

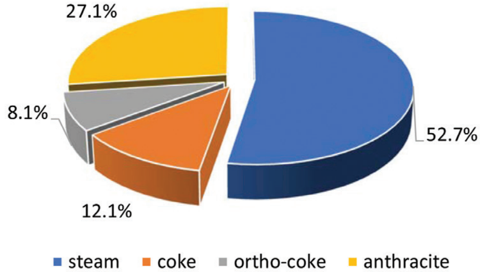

Fig. 8. Distribution of hard coal types in coal resources in Russia (Economy of Russia, 2017)

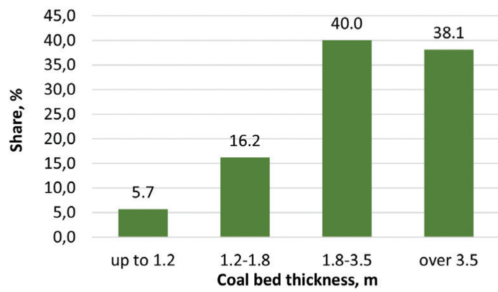

Fig. 9. Distribution of hard coal bed thickness in Russia

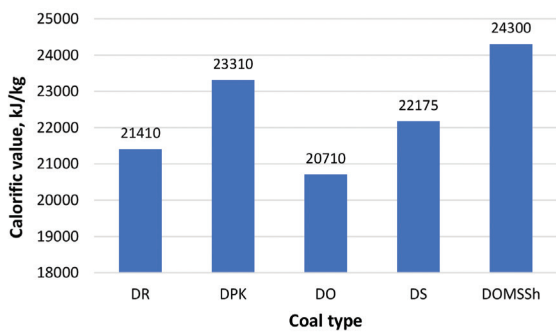

Fig. 10. Calorific value of coal types in Russia

The natural content of ash in Russian coal is estimated to vary between 5% and 38% depending on the source coal basin. For instance, the natural ash content in the Kuznieck Basin is from 5 to 34%, in the Pieczorsk Basin it is 31.4 to 38%, and in Siberia and the Far East it is 9.5 to 38% [7]. Most of the energy coal is processed before entering the market so the ash content is reduced to an estimated range of 3.6–10.1% depending on the coal type and degree of enrichment (Fig. 11).

The content of sulphur in Russian coal is close to that of Ukrainian coal and varies between 0.2% and 3.2%. The sulphur content in the energy coal after processing is estimated to vary between 0.2% to 1%.

The geological conditions indicate the need for changes in the excavation technologies that would result in better coal quality and the reduction of dust and other pollutant emissions.

The technologies need to be modified to reduce the over-excavation of the roof and the floor of the coal beds, thus minimising adding waste rock to the output. Therefore, the mines should plan to limit the excavation of thin beds and beds with high contents of intercalations, as well as excavation within fault zones, and beds with high ash and sulphur contents. This can be achieved by selective excavation with the use of plough systems or by abandoning parts of the coal deposit. However, considering the existing excavation systems, safety aspects and economic factors, it may be expected that the mining plants would have to, and would opt to, improve the processing rather than abandoning lesser quality resources. The cost and time of processing would certainly affect the final market price of the product.

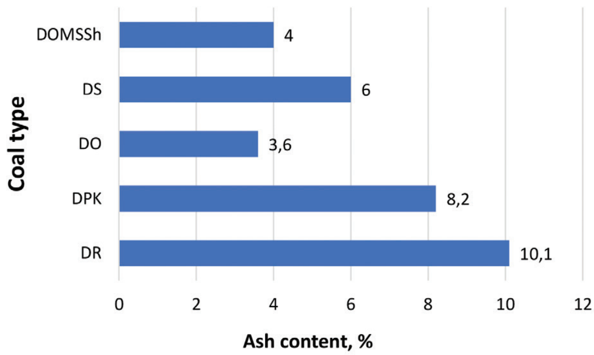

Fig. 11. Distribution of ash content vs. coal type in Russia

5. The situation on the coal market

5.1. Poland

In 2016, Poland consumed around 13.8 million tons of coal for the needs of individual households, of which 5 million tons was supplied from local mines and 8.8 million tons was imported coal mainly from Russia. These values show that individual households use more imported coal. Since the implementation of anti-smog regulation in the Silesia and Małopolska voivodships, the flotation concentrate and coal sludge were eradicated from the market leaving a gap in supplies of around 600,000 tons. In addition, the regulation by the Ministry of Development [21] regarding higher standards for coal furnaces will become binding in the year 2018. From then, the colloquially named 'smokers' ('kopciuchy' in Polish) – a common type of furnace that can burn coarse coal and any combustible waste – will no longer be on sale. New class 5 furnaces are equipped with an automated feeder and designed to only burn highly calorific coal culm with low sulphur and ash contents, or alternatively, a specially prepared coarser sort of coal e.g. a so-called 'eco-bean'. There is a very low availability of this type of coal in Poland [15].

Coal mines, especially those producing high quality energy coal (also used in households) are not able to increase production due to underinvestment. There has been no work carried out to access new resources over the last three years (besides at the LW 'Bogdanka' mine) due to EU anti-coal policy, unstable coal prices on the world markets (relative low in this period), and the reorganisation of coal companies in Poland. Furthermore, the main exporter of energy coal to Poland (the Russian Federation) cannot increase the supply because there is no production surplus that can be allocated for export. Due to this situation, Poland is seeking other sources of coal import from other countries. In 2017, there was the first delivery of coal from the United States, and commercial negotiations are underway regarding the import of coal from Kazakhstan and Columbia [17, 18].

In the abovementioned circumstances, during the peak time for the coal market (i.e. just before the heating season), the individual buyers had to pay 850 PLN for 1 ton of the popular coal type 'nut' [15]. According to the projections made by specialists, the price in December was expected to be 930 PLN, exceeded 1,000 PLN in February, and reaching 1,100 PLN in March (Fig. 12). Until now, due to the relatively gentle winter, the coal prices did not significantly increase comparing to September 2017, yet an increase of around 10% was recorded compared to the previous year. The coal culms of calorific value below 20 MJ/kg show the lowest prices, i.e. the largest producer in Europe – the Polish Mining Group (PGG) – offers the coal culm for 400 PLN per ton [28] (Fig. 13). The price for the 'nut' type is 627–784 PLN/ton, for the 'bean' type it is 615–775 PLN/ton, and for the 'cobble' type it is 701–790 PLN per ton. The most expensive are products branded 'eco', 'eco culm' and 'eco pea', the prices of which reach 900 PLN per ton (Fig. 13). Considering the pro-ecological EU policy, the prices of eco type products will certainly remain at the current level and may even rise.

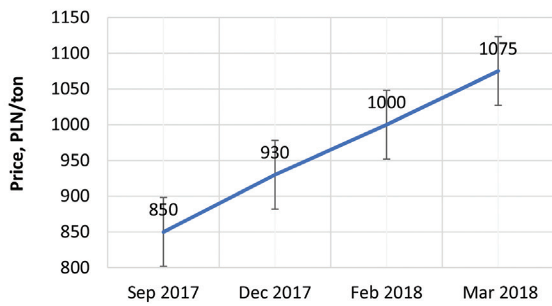

Fig. 12. Predicted rise of prices of 'nut' type hard coal in Autumn 2017

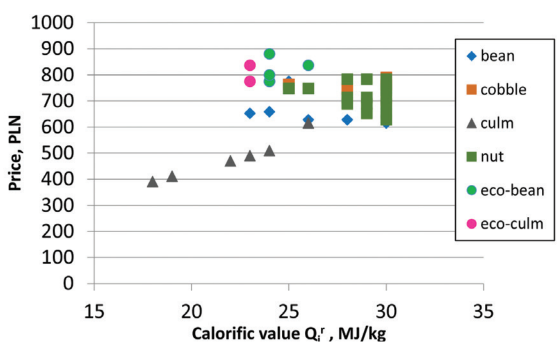

Fig. 13. Prices of coal in PGG – December 2017 [28]

It is important to note that the ash content in the offered coal is usually at a level of 5 to 10%, which also refers to eco-culms and eco-peas (Fig. 14). In the case of ordinary culms, it reaches 20 to 26%. The content of sulphur is most often less than 1% (Fig. 15). There is no apparent relationship between the product type and the sulphur content even though the highest sulphur content is found in coal culm.

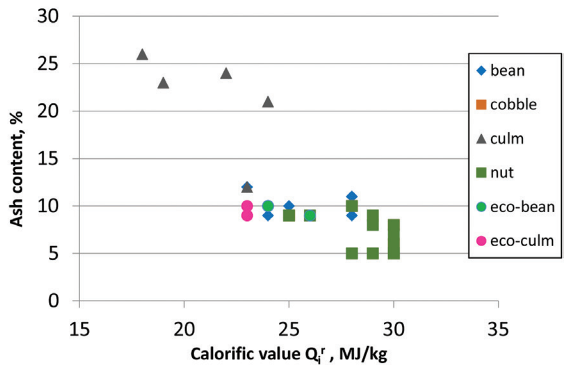

Fig. 14. Content of ash in the coal supplied by PGG – December 2017 [28]

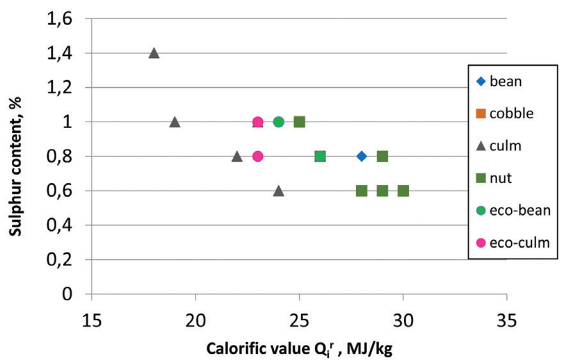

Fig. 15. Content of sulphur in the coal supplied by PGG – December 2017 [28]

5.2. Ukraine

Currently, Ukraine does not have any restrictive regulations with regard to the coal quality and furnace class used in households. Obsolescent types of furnaces and fire places that are used to burn coal and often domestic waste are common. Therefore, coal of low quality is abundant on the Ukrainian market.

The association agreement between the EU and Ukraine obliges Ukraine to adjust its regulations regarding emission to the European law, and in particular, regarding the combustion of solid fuels; this will certainly affect the coal prices. Currently, coal is offered for buyers at 250 PLN/ton (2,000 UAH) [16], this has an average calorific value of 20,500 kJ/kg, ash content 40% and sulphur content 3–5%. The average unit cost of extraction of 1 ton of such coal is 312 PLN (2480 UAH) in state-run mines, and 250 PLN (2000 UAH) in private enterprises.

However, its price strongly depends on the calorific value and is burdened with additional costs of the necessary processing (enrichment). The prices of coal allocated for households (gas-flame coal – type DG) versus the coal calorific value are presented in Fig. 16.

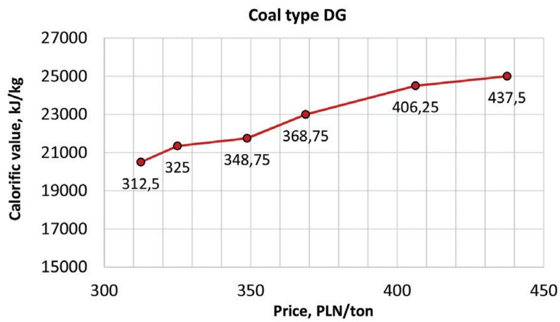

Fig. 16. Price of coal for households in Ukraine vs. calorific value

In the present political situation in Ukraine, the Lwów-Wołyń Coal Basin has become the main coal supplier, yet the quality of its coal is inferior to coal in the Donieck Basin. Today, only a fraction of mines in East Ukraine are on the territory controlled by the Ukrainian authority – 35 state-owned mines and 30 privately owned mines. These mines extracted 40.9 million tons of coal in the year 2016. In the territory controlled by the separatists, there are 97 mines; these are both state owned and privately owned (69 and 28 respectively), which constitutes 57% of the total number of mines. Despite seven of these mines being entirely closed and flooded, the production of coal on the separatist controlled territory was around 17 million tons in the year 2016 (12 million tons in the Donieck district and 5 million tons in the Ługańsk district). This coal is exported to Russia or, via middle agents to the West, mainly to the European Union as so-called 'coal of unknown origin'. This situation and the increasing demand has resulted in a deficiency of energy coal on the market in Ukraine, hence the need for coal imports. Coal imports to Ukraine in 2016 amounted to 15.6 million tons, and 22 million tons in 2017, while the cost of importing it almost doubled due to coal prices increasing on the world markets [27]. Among the countries exporting coal to Ukraine is Poland, who sent about 200,000 tons of this fuel in the previous year.

5.3. Russian Federation

The extraction of coal in Russia in the year 2017 was projected to reach approx. 400 million tons (4% more than in the year 2016), of which 310 mln tons is energy coal. The increase in production of the energy coal in particular is related to the growth in demand from external markets such as Turkey, Asian countries and the European Union [26]. By the end of 2017, the Russian Federation exported approximately 185 million tons of coal [19], and is recording steady yearly growth of exports by 8%.

Mining enterprises in Russia cannot rely on internal market demand from private consumers because the state controls prices for natural gas thus making gas a strong competitor on the energy market. Through this policy, the state encourages household owners to use gas for heating with the effect that less coal is burnt which reduces the emission of pollutants.

The price of energy coal according to KemUgleSbit [29] depends on the coal type and varies from 142 PLN (850 RUB) for 1 ton of fine fraction 0-50 mm coal (DOMSSh – flame culm coal II) to 225 PLN (1,100 RUB) for 25-200 mm fraction coal (DO – flame coal nut II), up to 242 PLN (1,450 RUB) for 1 ton of so-called 'eco-bean' type (DS – flame coal eco-bean I). The current prices of coal in Russia versus coal type are presented in Fig. 17.

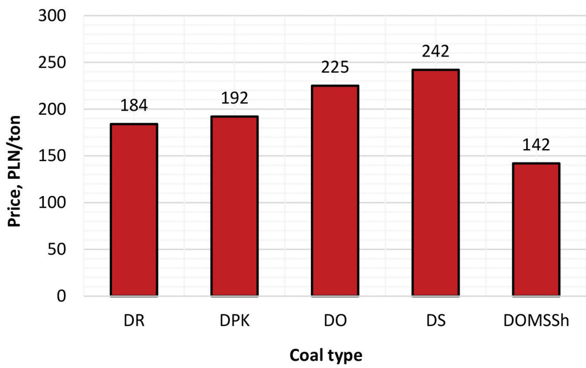

Fig. 17. Prices of energy coal in Russia – breakdown by coal type:
DR –flame coal unsorted; DPK –flame coal cobble II; DO – flame coal nut II;
DS – flame coal bean I; DOMSSh –flame coal fine grained – culm II

Summarising the review, it may be pointed out that the prices of energy coal for household use in Russia and Ukraine are much lower than in Poland, in the region of a half to a third. This situation arises from the fact that in the Ukraine the difference between unit production cost and unit price for 1 ton of coal is compensated for from the state budget. Whereas in Russia, the coal mining industry not only meets the local market demand for energy coal in 100% but provides a surplus that is designated for export. In addition, Russia controls and lowers the price of natural gas which in turn, affects coal demand.

In the case of import of the coal from the Ukraine or Russia, it needs to be considered that the final price is subject to custom duty, cost of transport and the middle agent's margin. The resulting price of the coal imported to Poland is close to the price of locally produced coal. With respect of the main quality parameters of energy coal, such as calorific value, ash content and sulphur content, the local coal is practically of the same quality as Ukrainian or Russian coal. In many cases, Russian or Ukrainian coal may contain slightly more ash or sulphur, yet this is negligible and should not present a barrier to the importation of the coal.

6. Effect of coal quality on dust emission

Coal is still the main source of energy for individual households. Approx. 60% of the households use coal furnaces compared to only 34% of gas burners, according to the statistically representative poll carried out by Czerski and Mirowski [1] in 14 communes in the Małopolska voivodship. Sulphur and nitrogen compounds, then carbon monoxide and dioxide followed by dust are the main contributors to overall emission [8]. The other pollutants are organic compounds, such as polycyclic aromatic hydrocarbons (benzo-(α)-pyrene), dioxins, furan, aliphatic hydrocarbons, aldehydes, ketones, as well as heavy metals [6]. These toxic substances are formed during the combustion of mostly inferior quality coals, e.g. low caloricity coal sludge. It is apparent that the calorific value is closely dependent upon the ash content in the coal. The research conducted in Ukraine shows that the dependency between these two parameters is logarithmic and of very high coefficient of determination (99%) [24] (Fig. 18). The natural ash content in hard coals varies from 10 to 13%; however, as mentioned earlier, due to the geological conditions and applied technology, the ash content in the extracted coal rises to 40–45%. Therefore, the coal needs to be processed before entering the market, which affects the final price.

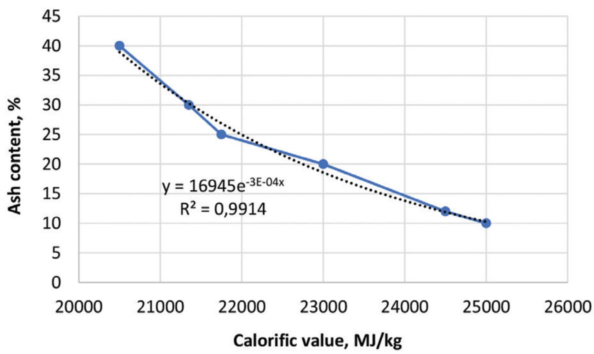

Fig. 18. Relationship between calorific value and ash content in the coal [24]

Dust (particulate matter – abbr. PM) is the air pollutant defined as a mix of particles of solids and liquids, suspended in the air, and consisting of organic and inorganic substances. It may include many chemical substances harmful to man. The chemical composition of dust closely depends on the source of the emission, the season of the year, the meteorological conditions including prevailing wind direction, and characteristics of emissions in the area under consideration [6]. It needs to be highlighted that the dust emission from the burning of coal that is mostly felt and recorded in autumn and winter makes up only a part of the overall dust emission. Coal-related dust emission has also risen due to this fuel being used in low power output, low efficiency furnaces which lack dust filters (domestic heating furnaces, tiled stoves, etc.). The Institute For Chemical Processing Of Coal in Zabrze conducted the research [11], which investigated the effect of the furnace type and the so-called top and bottom coal combustion on dust emission. The authors of the research concluded that the top combustion does not reduce dust emissions in general because it showed a reduction in 40% of the tested cases while in 25% of cases, it significantly increased the emission. A chamber type furnace emits from 279 to 1,322 tons of dust when burning 1 m^3 of 'nut' type of coal, whereas a so-called 'goat' ('koza' in Polish) type of furnace produces 821 to 848 tons of dust from 1 m^3 of coal. Therefore, furnace design alone may reduce the dust emission by around 75%.

The calculus for estimation of the dust emissions during coal combustion in furnaces of known power output is determined in '*Indexes of pollution...*' 2015 [25]. The general equation for estimation of dust emission based on the emission index of the fuel, which is as follows:

$$E = B \times W_o \times W$$

where:

E – emission of substance, g/ton,
B – fuel consumption, kg,
W_o – calorific value of fuel, kJ/kg,
W – emission index per giga-Joule of chemical energy of the fuel.

In case of coal the W index is defined:

- for fixed grating and natural drought – $1000 \times A^r$,
- for fixed grating and forced drought – $1500 \times A^r$,
- for mechanical grating – $2000 \times A^r$;

where: A^r – content of ash in %.

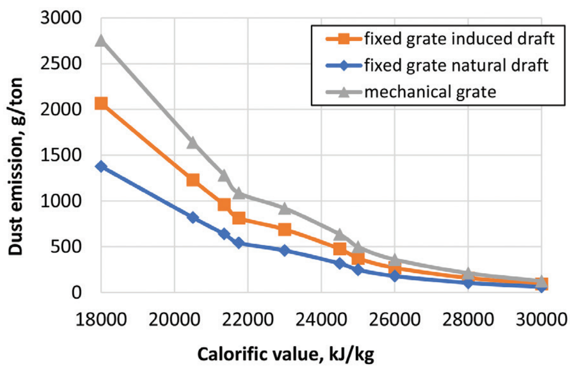

Fig. 19. Relationship between dust emission and calorific value of coal

An analysis was carried out to demonstrate how the calorific value parameter and type of grating affects the dust emission. The analysis included the research on calorific value – ash content relationship presented in Fig. 18. The calculation for theoretically burning 1 ton of coal shows, as expected, that the higher the calorific value of the coal, the lower the emission (Fig. 19) – this drops down to 0.1–0.2 kg at a calorific value of 27,000–28,000 kJ/kg. Moreover, at such high calorific values, the differences of dust emission for different types of gratings are insignificant. Thus, the procurement and use of coal of a calorific value of 27,000 kJ/kg or higher greatly reduces the emission of dust to the atmosphere. It has to be pointed out that the use of coals of a calorific value below 22,000 kJ/kg causes much higher dust emission which even worsens in case of low calorific coal culms. Furthermore, at a calorific value of Q = 19,700 kJ/kg and using the most efficient gratings, the dust emission per 1 ton of coal is higher than 1 kg (Fig. 19), while at calorific value of 18,000 kJ/kg and using a mechanical grating, the emission reaches 2.8 kg.

The best designed furnaces currently available on the market are the furnaces with automated feeders, yet these remain a small fraction of all appliances [1]. They are designed to burn 'eco-bean' ('ekogroszek'), 'eco-culm' ('ekomiał') and regular culm. Efficiently burned culm emits more dust than efficiently burned good quality coals, yet still less than good quality coal burnt in low efficiency furnaces. The Polish Standard PN EN 303–5:2012 [14] imposes the Class 5 rating for new furnaces; this is characterised by high efficiency resulting from the automated supply of air and fuel, and from the use of a top combustion chamber. The new requirements regarding furnaces have been provided by the Minister of Development and Finance in his regulation [21] and they have been valid since 1st July 2018.

The class of furnace is also defined by the type of fuel it is designed for. Figure 20 depicts the relationship between the efficiency of the furnace and its power output (percentage of the nominal power of the furnace). The highest-class furnaces achieve maximum efficiency at just 20% of the nominal power output, Class 4 at 50%, and only Class 3 at 75% power output. The old type furnaces usually have a much lower power output. It needs to be noted that according to the already outdated standard PN-EN 12809 from 2002 [13], the furnaces possible efficiency was not higher than 70–74%, hence there is a systematic rise in quality and efficiency of furnaces.

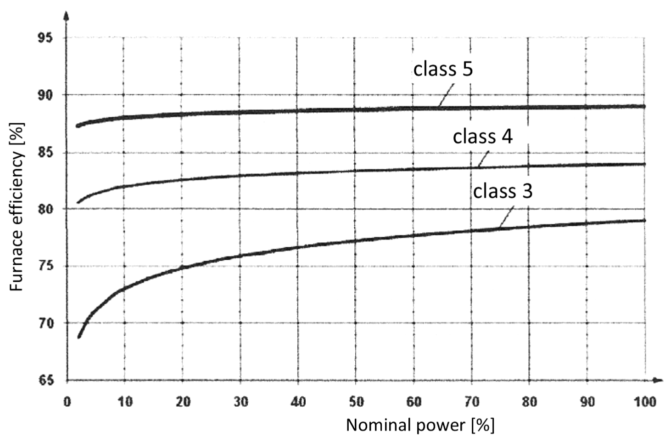

Fig. 20. Efficiency of the highest class furnaces versus power output – in compliance with Polish Standard PN EN 303–5:2012 [14]

In the case where the furnace is equipped with an emission reducing appliance (e.g. an electro-filter), the nominal power is reduced, hence an efficiency less than 100%. Czerski and Mirowski [1], by calling on research by EMEP/EEA Air Pollutant Emission Inventory, demonstrate that just inappropriate use of the furnace or defective installation of a central heating system reduces the efficiency of the furnace to 50–65%. The reduction of efficiency has an immediate impact on coal consumption and the related emission of dust and the volume of ash. The calculations were carried out specifically to demonstrate the effect of the efficiency of the heating appliance with regard to the amount of coal burnt during the heating season. It was assumed for this purpose that the heating season lasts 200 days (i.e. from the middle of September until the end of March – according to the definition by regulation Journal of Law 2007, Item 92 [20] – '…season, when atmospheric condition necessitate continuous generation of heat to warm up premises'), and the heating furnace used is of 20 kW power, which is sufficient to heat an average 170 m^2 house. It was further assumed that the furnace works for ten hours per day at a power output of 70% of the nominal power, and its efficiency is 0.89 – Class 5 furnace, 0.84 – Class 4 furnace, 0.78 – Class 3 furnace, or 0.52 – defectively installed or incorrectly set up furnace. The ash content in the coal was presumed to be 5–26% i.e. the range specified in the selling offer by the Polish Mining Group [28].

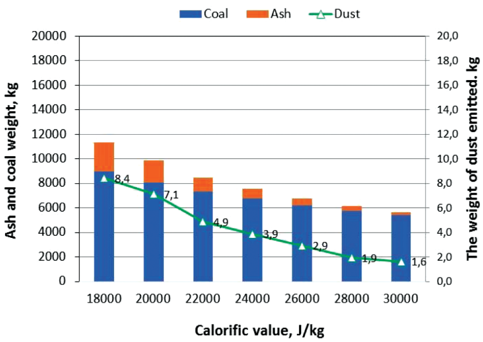

Fig. 21. Coal consumption, amount of ash and dust emission at furnace efficiency η = 0.89

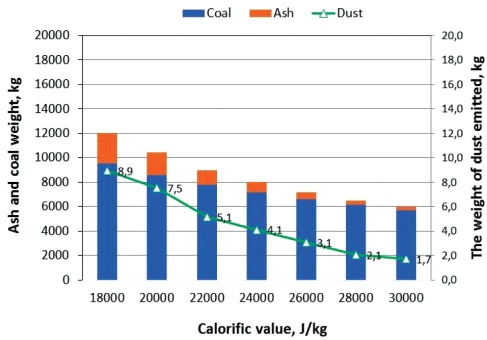

Fig. 22. Coal consumption, amount of ash and dust emission at furnace efficiency η = 0.84

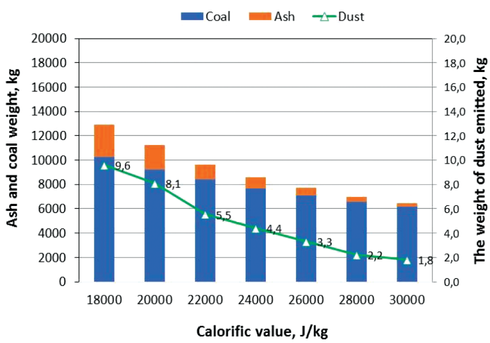

Fig. 23. Coal consumption, amount of ash and dust emission at furnace efficiency η = 0.78

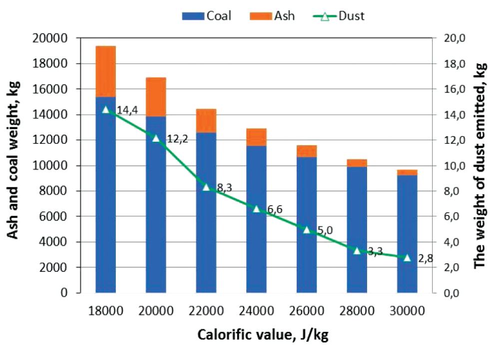

Fig. 24. Coal consumption, amount of ash and dust emission at furnace efficiency η = 0.52

The results of the calculation show an increase of coal consumption at lower furnace efficiency and an increase of dust emission even though coal of highest calorific value is used. The consumption of low calorific coal in the furnaces with an efficiency of η = 0.78-0.89 is estimated as 8,989 kg for the heating season at η = 0.89, and up to 10,256 kg at η = 0.78 (Fig. 21–23). The use of high calorific coal results in a significant drop in coal consumption. The use of coal with a calorific value of 24 MJ/kg reduces the consumption to 6,742 kg (for η = 0.89) and 7,692 kg (for η = 0.78) respectively, whereas the use of 30 MJ/kg caloricity coal reduces the consumption to 5,393 kg and 6,154 kg for η = 0.89 and η = 0.78, respectively. Therefore, the amount of coal needed to heat up the modelled house is reduced by half comparing to low calorific coals. At the same time, the use of high calorific coals reduces the amount of ash by approx. nine times, while the dust emission in case of η = 0.89 furnace will amount to 8.4 kg for culm with a 18 MJ/kg calorific value, yet just 1.6 kg for coal with a calorific value of 30 MJ/kg.

The situation appears entirely different in the case when the efficiency of the furnace in use is $\eta = 0.52$. At such a low efficiency, the consumption of coal increases by more than 50% (Fig. 24) irrespectively of the calorific value of the coal; thus, in the case of coal culm, this will amount to 15,385 kg, and in case of highly calorific coal, it will amount to 9,231 kg. In addition, the coal culm generates 4 tons of ash, while the 30 MJ/kg coal generates almost 0.5 ton of ash. The dust emission increases to 14.4 kg and 2.8 kg for coal culm and 30 MJ/kg coal, respectively.

Generally, assuming that the average user who does not yet possess the modern generation furnace of efficiency $\eta = 0.78$, and applies 'bean' or 'nut' types of coal of 26,000 kJ/kg caloricity, burns approx. 7 tons of coal in the heating season, disposes around 640 kg of ash and emits around 3.3 kg of dust into the atmosphere. Therefore, it consumes half the amount that would be needed in the case of coal culm and emits a quarter of the amount of dust.

Educational and informational programs aimed at the consumers should be delivered to promote use of coal with a calorific value of at least 27,000 kJ/kg.

7. Summary

The article presents an analysis of geological conditions, hard coal quality parameters and the coal market situation in Poland, Ukraine and Russia. The geological condition of coal basins in all three countries are generally similar, yet the thin-bedded deposits are more often found in Ukraine. There are no practical differences in the quality parameters of energy coals in these countries. The only difference between Polish, Ukrainian and Russian coals is usually a higher content of sulphur in the coal from Poland's Eastern neighbours.

One of the imperatives of mining enterprises is minimising impact on the environment during the exploitation process as well as at the coal consumption stage. Therefore, certain measures can be undertaken at the production stage to reduce the content of waste rock and solid particles in the output coal. One such measure, leading to lessening the environmental impact, is the development and implementation of excavation methods for the reduction of the over-excavation of rocks at the roof and floor of the coal bed. These methods are essential for the excavation of thin-bedded deposits. The other measure is the limitation of the exploitation of coal beds with high sulphur and ash content, as well as beds with numerous intercalations and tectonically disturbed beds. It needs to be noted that generally, the Russian and Ukrainian coal deposits are not much different from Polish deposits in the aspect of quality; thus, it is unnecessary to introduce any pro-quality constraints on the import. In particular, the coal offered for sale contains less sulphur and ash due to processing by the producers. However, the cost of the processing adversely affects the final price for the consumers.

Despite comparable quality parameters, the prices of coal for household use in the analysed countries are very much different. While in Russia, the price for coarse coal is 142 PLN (850 RUB) per ton, one needs to pay 420 PLN for the same coal type in Poland. The price of this type of coal in Ukraine is 320 PLN (2,500 UAH) which is significantly lower. The prices of the coal imported to

Poland, after taking into account all costs related to custom fees, transport and the agent's margin, becomes comparable to local coal prices. Nevertheless, Poland imported around 6 million tons from Russia in 2017, of the 9 million tons that was the overall import. It is noteworthy that Russian coal is practically offered for sale only at fuel storage yards, and mainly for household use. Therefore, cutting out the middle agent's margin would substantially reduce the price of the coal.

The key element in this analysis – the calorific value of coal and its relation to ash content – still needs to be addressed. The changes in the law related to limitations of sales of coal sludge and flotation concentrate is a very positive solution that significantly reduces dust emissions into the atmosphere. The computational simulation of dust emission for furnaces of various types of gratings shows that even the best designed furnaces emit large amounts of dust when burning coals of calorific values less than 22,000 kJ/kg, i.e. exceeding 1 kg of dust per one ton of coal. In contrast, burning coal of calorific values of 27,000 kJ/kg, or higher, considerably reduces the dust emission irrespective of the grating type.

The simulation of coal usage in furnaces of various efficiency levels shows that burning bad quality coal in a furnace of efficiency $\eta = 0.89$ has the same environmental impact as burning highly calorific coal in a furnace of $\eta = 0.52$ efficiency. Furthermore, the use of the high calorific coal reduces the generation of ash by approx. nine times, while the emission of dust from an $\eta = 0.89$ furnace in the heating season, for coal culm of 18,000 kJ/kg is 8.4 kg, and just 1.6 kg when using 30,000 kJ/kg coal in the same furnace. The calculation demonstrates that the coal consumption for seasonal heating of 170 m^2 house is approx. 6.5 tons, assuming the calorific value of coal to be 28,000 kJ/kg, and not the best yet well-functioning furnace of 74% efficiency, whereas in the case of the use of 18,000 kJ/kg coal culm, more than 10.5 tons of the fuel is required. In the second case, the burnt fuel leaves almost 3 tons of ash and the dust emission is 10 kg per ton of coal culm. The concern is that to date, the modern, Class 5 furnaces remain rare; the old types and Class 3 and 4 furnaces are more common. Efficiency of the older devices is usually low and slightly above 50%, hence the actual coal consumption per heating season, as well as the amounts of ash and dust, being higher than calculated. However, the analysis proves that the use of coal with a calorific value of at least 27,000 kJ/kg, irrespective of the source, and in various designs and type of furnaces, considerably reduces both the generation of ash and the emission of dust. Therefore, it is strongly recommended that the coal producers should offer more coal types that are environmentally friendly, while the furnace manufacturers should offer models designed for burning coal of the highest quality.

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Measurements and simulation of CO_2 concentration in a bedroom of a passive house

Pomiary i modelowanie stężenia CO_2 w sypialni domu pasywnego

Abstract

This paper presents the results of the measurements and simulation of carbon dioxide concentration, as an indicator of indoor air quality, inside the master bedroom of an inhabited passive house. The measurements were taken in the autumn for a period of ten days. A series of sensors placed inside of the test object wirelessly measured the contaminant concentration every thirty seconds. The measurements were taken continuously in real time, when the occupants freely used the household. The contaminant concentration shows the impact of their activity on the air quality, as they were the only indoor air source of CO_2. During the measurements, the ventilation system that the house was equipped with was manually controlled by the users according to their daily routine. Simulations were performed to determine if it was possible to recreate the measured conditions within the bedroom of the passive house. The chosen program was the CONTAM software application, a tool designed for indoor air quality and ventilation analysis, developed by NIST.
Keywords: CO_2 concentration, passive house, indoor air quality, multi-zone model, CONTAM

Streszczenie

W artykule przedstawiono wyniki pomiarów i modelowania stężenia dwutlenku węgla, jako wskaźnika jakości powietrza wewnętrznego, w sypialni zasiedlonego domu pasywnego. Pomiary prowadzono w okresie jesiennym, nie zaburzając normalnego cyklu życia domowników. Umieszczone wewnątrz obiektu testowego czujniki w sposób bezprzewodowy mierzyły poziom stężenia zanieczyszczenia co 30 sekund, przez okres dziesięciu dni. Pomiar był dokonywany w sposób ciągły, w warunkach i czasie rzeczywistym, gdy mieszkańcy swobodnie poruszali się wewnątrz budynku. Poziom stężenia dwutlenku węgla odzwierciedlał wpływ aktywności mieszkańców na jakość powietrza wewnętrznego, gdyż byli oni jedynym źródłem CO_2 w obiekcie. Podczas pomiarów instalacja wentylacyjna, w którą dom został wyposażony, była włączona i regulowana przez domowników według wypracowanego przez nich schematu. Przeprowadzone symulacje miały na celu określenie czy możliwe jest odtworzenie warunków zmierzonych w sypialni analizowanego budynku. Do modelowania wybrano oprogramowanie CONTAM, narzędzie przeznaczone do analizy systemu wentylacji i jakości powietrza wewnętrznego, opracowane przez NIST.
Słowa kluczowe: stężenie CO_2, dom pasywny, jakość powietrza wewnętrznego, model wielostrefowy, CONTAM

1. Introduction

The building sector, followed by the industry and transport sectors, is the largest energy-consuming sector [1]. To control the energy use of new buildings, European directives require that all new buildings in the European Union must be near zero energy from 31st December 2020 and public buildings must be near zero energy from 31st December 2018 [2]. Because of these regulations, and due to increasing energy prices, the trend to build more energy efficient dwellings is growing.

The passive building standard is one of the most advanced forms of energy-efficient building standards. Houses built in line with this standard are objects that maintain a proper indoor climate in the summer as well as in the winter without the need for conventional heating and cooling systems [3]. The basic goal of the passive standard is to minimise thermal loss of the object to such an extent that the heating system uses a minimal amount of energy. In central Europe, for an object to be classified as passive, the amount of energy used for heating purposes should not exceed 15 kWh/(m^2 year) and the primary energy demand for the whole object (including heating, hot water preparation, electricity, etc.) should not be over 120 kWh/(m^2 year).

To meet such high energy standards, passive objects have a very compact structure and are well insulated. The outer envelope of the building is extremely airtight in order to minimise the uncontrolled airflow between the building and the outdoor air. The air exchange is limited to n50 = 0.6 1/h (0.6 of the volume of the whole building in one hour) and is certified by a blower door test [4]. Great attention is placed on the heat recovery of such objects as it must be at least 75%. Because of these rigorous standards, air exchange through the building envelope is minimised and fresh air is no longer provided by a natural ventilation system but by a mechanical ventilation system that allows heat recovery from the discharged air. Additionally, such objects may be equipped with a ground heat exchanger that heats or cools the fresh air before it flows into the ventilation system. This allows energy savings and may prevent passive objects from overheating in the summer.

Because of their airtight structure and minimal infiltration through the building envelope, passive objects may be prone to the accumulation of contaminants; however, they are equipped with mechanical ventilation systems, which should provide proper air exchange. This paper presents the results of measurements and simulation of carbon dioxide, as an indicator of indoor air quality, inside the master bedroom of a passive house. The measurements were conducted to determine if the quality of the indoor air of the test object meets the hygienic standards. During the measurements, the ventilation system with which the house was equipped was manually controlled by the users according to their daily routine. The measurements were taken continuously in real time, when the occupants freely used the household. The contaminant concentration shows the impact of their activity on the air quality, as they were the only indoor air source of CO_2. To identify whether it was possible to reflect the measured conditions within the test object through use of a computer program, simulations were performed using the CONTAM software application, developed by NIST, which is a tool designed for indoor air quality and ventilation analysis. The results of the conducted simulations allowed discussing the influence of the changing conditions within the bedroom (e.g. the number of persons, the ventilation air flow rate, the position of doors) on the indoor air quality.

The problem of carbon dioxide concentration in bedrooms has been researched by authors in the past. Kotol et al. [5]and Bekö et al. [6] analysed the concentration of carbon dioxide within houses built in accordance with the classic building standard with a natural ventilation system. The former measured the concentration of carbon dioxide within bedrooms in seventy-nine Greenlandic households, while the latter analysed the concentration of the same contaminant inside the bedrooms of five hundred Danish children. Both studies showed that the concentration of carbon dioxide exceeded the maximum hygienic levels; the main reason, highlighted by the authors, was the lack of the proper airing out of the test objects. Sekhar & Goh [7] studied the difference in the indoor air quality in bedrooms with a natural ventilation system and an air-conditioning system. The concentration of the contaminant was higher in the latter case due to the use of split-system air-conditioning units that only recirculate air and do not provide fresh outdoor air. They also found that the CO_2 level could affect the duration of sleep: if the concentration of CO_2 was high, sleep duration would decrease. The effects of bedroom air quality on sleep and performance during the following day was thoroughly examined by Strom-Tejsen et al. [8], who conducted two field-intervention experiments in single-occupancy student dormitory rooms. They concluded that when the CO_2 level was lower during the night, objectively measured sleep quality improved significantly. The study also showed that sleepiness reported the next day was lower and the ability to concentrate and the subjects' performance during a logical thinking test improved. The authors underlined that these factors can be significantly improved by increasing the supply rate of clean outdoor air in the bedrooms. Additionally, Gładyszewska-Fiedoruk [9] analysed the concentration of carbon dioxide within the bedrooms of a detached house, built in the classic standard, with natural ventilation. The study showed that the concentration of carbon dioxide exceeded the maximum recommended value most likely when more than one person slept inside the tested bedroom. This happened regardless of the sex and age of the occupants. The author underlined the risk of accumulation of contaminants in the case when there are too many occupants in relation to the possibility for bedroom ventilation. Batog & Badura [10] measured CO_2 levels in Polish sleeping rooms (typical blocks of flats with low ventilation rates). They also conducted CFD simulations in which they studied the dynamic changes of CO_2 in bedrooms. The results of their experiment showed that in a typical small bedroom, the air quality was very bad and in most cases, the CO_2 levels significantly exceeded the recommended hygienic standards. Based on the results of their research, the author recommended applying demand-controlled ventilation using sensory information rather than systems based on designed air exchange rates. They saw it as the only proper way to provide both good air quality and good energy efficiency in buildings.

2. Background

2.1. Analysed passive house

The research object (Figs. 1, 3 and 4) is located in a small town in the south west of Poland in the Silesian region [11]. The object is a detached house with a ground and first floor with the area of 120 m^2 (Fig. 1) [12]. The building meets the strict passive house standards, certified by the Passive House Institute [13]. Its annual maximum space heating demand is below 15 kWh/(m^{2}a). The blower door test performed before the inhabitants moved in, gave the result of 0.36 1/h and later, after the house had been occupied, 0.5 1/h. The building also has the typical characteristics of a passive house. Solar heat gain is increased by placing the windows with a high solar transmittance of glazing mainly within the south elevation. An exception is one window on the west elevation, upon which the main entrance doors are also located. All windows, with the exception of a glass door leading to a terrace, are fixed with no possibility of opening. The ventilation of the building is mechanical. The object is seated on a 25 cm reinforced concrete slab, underneath which, a 40 cm layer of Styrofoam was placed; as a result, the thermal bridges that would have occurred between the ground and the house were prevented. The thick layer of thermal insulation limited the heat exchange between the house and ground to almost zero. The space-heating energy demand of the passive house is covered by the floor heating system and by the warm air of a central mechanical ventilation system. The thermal energy for heating purposes (floor heating system, air heating coil) as well as for domestic hot water production is provided by the ground-source heat pump.

Because of the lack of fresh air infiltration through the building envelope and the fact that air is supplied only by a mechanical ventilation system, it was decided to measure the concentration of carbon dioxide within the described passive house. This was done to determine if the quality of the indoor air of the test object meets the recommended standards.

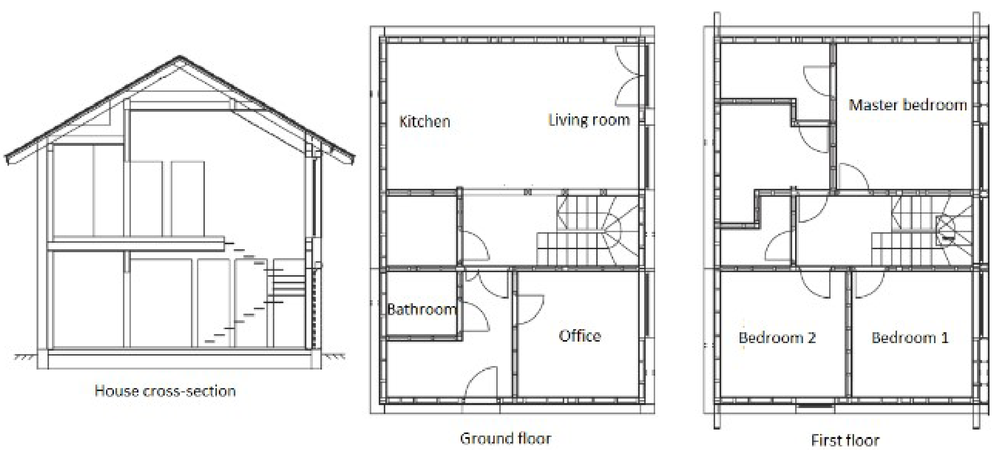

Fig. 1. Test object – plan of the passive house

During the research project, the house was occupied by a family of five: two adults and three children. One of the adults had a full time job which required his presence outside of the house, the other adult had a part time job that was done from within the house. Two of the children attended school during the research timeframe while the youngest child stayed at home under the second adults supervision. The occupants were the only indoor air source of carbon dioxide as cooking and water heating was done using an electrical system and heat pump, respectively. During the experiment, the inhabitants freely occupied the house and maintained a normal daily routine.

The research project focused on the measurements of carbon dioxide as an indoor air quality indicator. A series of sensors (Fig. 2) were placed inside the test object and measured the CO_2 concentration as well as the temperature and relative humidity. The measurements were taken in the autumn, when school activities took place, for a period of ten days. The sensors wirelessly traced the measured parameters every 30 seconds. The range of installed sensors in terms of carbon dioxide concentration was 0-5,000 ppm and their accuracy was ±50 ppm. The airflow though the inlets inside the house was measured using a Balometer that had a range of 10-400 m^3/h and an accuracy of ±3%.

Fig. 2. Measuring equipment and sensors

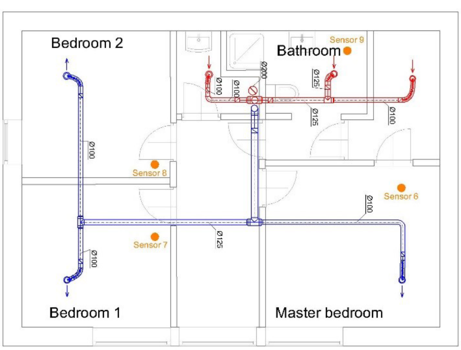

Fig. 3. First floor – sensor layout

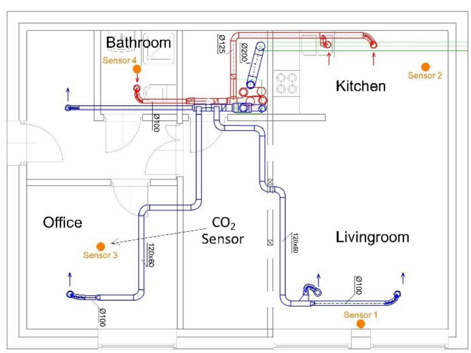

Fig. 4. Ground floor – sensor layout

The layout of the sensors (four on each floor) is shown in Figs. 3 and 4. The sensors were placed in rooms which were frequently occupied by the inhabitants. They traced the concentration of the contaminant continuously during the day and night. Measurements that took place during the night were done especially to determine if contaminant accumulation occurred in the bedrooms, as described in papers by Kotol et al. [5] and Bekö et al. [6] and Gładyszewska-Fiedoruk [9]. The risk of such an occurrence was high, as occupants reported that the night ventilation airflow rate was generally lowered to a minimum to eliminate noise.

2.2. Carbon dioxide

Carbon dioxide is a natural component of the earth's atmosphere. Its concentration in the outdoor air is around 0.04% (400ppm). The maximum indoor concentration of carbon dioxide that should not be exceeded, recommended by ASHRAE [14] and the World Health Organization, is 1,000 ppm [15]. This is also known as the *Pettenkofer* number. Higher concentrations of CO_2 have been proven to have a negative effect on human performance, the perception of poor indoor air quality and the prevalence of certain health symptoms such as the irritation of mucous membranes, headaches and tiredness [16–22]. The influence of elevated CO_2 concentration on the human body is presented in Table 1 [23, 24].

Table 1. Influence of elevated CO_2 concentration on the human body

CO_2 concentration [%]	CO_2 concentration [ppm]	Influence of elevated CO_2 concentration on the human body
0.2	2,000	occupants with respiratory disease may experience coughing or even fainting
1	10,000	increased respiratory rate
2-3	20,000-30,000	shortness of breath, deep breathing
5	50,000	breathing becomes heavy, sweating, pulse quickens
7.5	75,000	headaches, dizziness, restlessness, breathlessness, increased heart rate and blood pressure, visual distortion
10	100,000	nausea, vomiting, loss of consciousness within a few minutes
above 10	above 100,000	rapid loss of consciousness, coma, death

The results of the conducted measurements showed that the concentration of carbon dioxide in the analysed passive house remained below the level of 1,000 ppm for most of the time. However, periodically repeating exceedances of the maximum hygienic level occurred in every test room of the passive house. These periods were characterised by different lengths and times of occurrence, reflecting the rhythm of the occupants' lifestyles. A regularity in the fluctuations of the contaminant can be seen. The concentration of carbon dioxide rises during the day and lowers during the night on the ground floor while the opposite occurs on the first floor, which is strongly connected with the rhythm of the day and night.

The longest exceedances of CO_2 concentration were noted in the master bedroom of the analysed passive house, where the two adults and the youngest child slept, which is why it is studied in detail in this paper.

To see whether the outdoor air had a negative impact on the inside air quality, an additional sensor was placed in the inlet of the ventilation system. The measured concentration of the contaminant in the outdoor air differed between 312 ppm and 450 ppm, with an average of 385 ppm (which corresponds to the literature values), meaning that it did not have a large impact on the concentration of the contaminant within the house. The measured average value of CO_2 in the outdoor air was also used in the conducted simulations and described in this paper.

2.3. Simulation

The aim of the conducted simulations was to determine if it is possible to recreate the conditions inside of the test object and to what extent. The chosen simulation program, CONTAM, developed by NIST (the National Institute of Standards and Technology), is a multi-zone indoor air quality and ventilation analysis program that allows the user to determine the following factors: contaminant concentrations; personal exposure in buildings; airflows, including infiltration, exfiltration, and room-to-room airflow rates; contaminant concentrations including the transport rate of airborne contaminants due to airflow [25]. In this paper, CONTAM version 3.2 was used. A transient simulation using the impact Euler solver was conducted for a period of ten days for each case.

The influence of occupancy schedules and the effectiveness of ventilation on the contaminant concentration inside the master bedroom of the studied passive house was analysed using the CONTAM software. The computer simulations were compared to the measurement results.

CONTAM software has been applied by, among others, Yu et al. [26] where it was used to conduct a transient simulation of carbon dioxide emission from the human body. The authors analysed the variety of the concentration of indoor carbon dioxide in an office room over time under steady-state conditions of natural ventilation based on CONTAM. Alonso et al. [27] designed an airtight apartment model using the CONTAM software in which the impact of three different ventilation systems were tested. Rim et al. [28] defined the influence of outdoor particle sources on indoor air quality under three different ventilation scenarios using the same software. These examples show that the program is suitable for modelling indoor air quality.

During the simulation, the entire household was taken into consideration. The occupants had a detailed occupant schedule that determined their whereabouts inside the house. The detailed schedule is shown in [29]. This was performed to determine how the contaminants from other zones influenced the concentration inside the tested master bedroom. As stated earlier, three out of the five occupants slept in the master bedroom. In the simulation, it was assumed that the occupants were inside the test room as follows:

- The male adult: from 10 pm to 6 am;
- The female adult: from 10 pm to 6:45 am;
- The child: 2 pm to 4 pm (nap) and 9 pm to 7 am.

The occupancy schedule was discussed briefly with the occupants as well as being analysed using the measurement results. During the rest of the day, the occupants moved throughout the house or outside it. During the night, the other two children slept in their bedrooms (bedroom 1 and 2).

For simulation purposes, the amount of carbon dioxide generated by the adult occupants during the day was 0.005 L/s during the day and 0.0033 L/s during the night, these levels were adopted from Persily [30]. The CO_2 generation rate relating to the children was assumed as 0.0038 L/s during the day and 0.0025 L/s while sleeping [30].

3. Measurement results

The results of the measurements of carbon dioxide concentration in the master bedroom of the analysed passive house are shown in Fig. 5. A pattern can be observed in fluctuations of the contaminant. The concentration of carbon dioxide rises during the night and lowers during the day. Significant periods of concentration of carbon dioxide exceeded 1,000 ppm usually last 7-8 hours and are connected with the time of night rest. These distinctive periods of exceedance were recorded for most of the nights in the considered period. The maximum values of concentration of CO_2 during the night were usually around 1,200 ppm; one occurrence of 1,500 ppm and one occurrence of 1,800 ppm were registered.

To determine the influence of the ventilation system on the concentration of carbon dioxide in the master bedroom, the air supply rate, supplied by the ventilation system, and the contaminant level measured inside the bedroom were compared in Fig. 5. This figure shows that the concentration of carbon dioxide is strictly connected to the amount of air that flows through the ventilation system. When the ventilation rate is high, the concentration of the contaminant significantly lowers and the highest concentration is observed when the ventilation rate is the lowest.

The occupants could control the airflow rate of the system using a manual control panel. This panel allowed them to change the supply rate to three different levels without the option of turning the system completely off. During the measurements, the occupants freely changed the ventilation rate according to their will without any interference from the authors. The occupants reported that the night ventilation airflow rate was often lowered to a minimum to eliminate noise.

The analysed master bedroom had two doors: one leading into the walk-in wardrobe and the other into the hallway. According to the occupants, they slept with the open door to the walk-in wardrobe, but the door to the hallway was sometimes open and sometimes closed.

The measured average concentrations of the CO_2 in the master bedroom of the passive house are comparable with the measurements shown in the research done by [9], which analysed the concentration of carbon dioxide within the bedrooms of a detached house, built in the classic building standard with natural ventilation. The study showed that the concentration of carbon dioxide were most likely to exceed the maximum standard when more than one occupant slept inside the test room. This happened regardless of the sex and

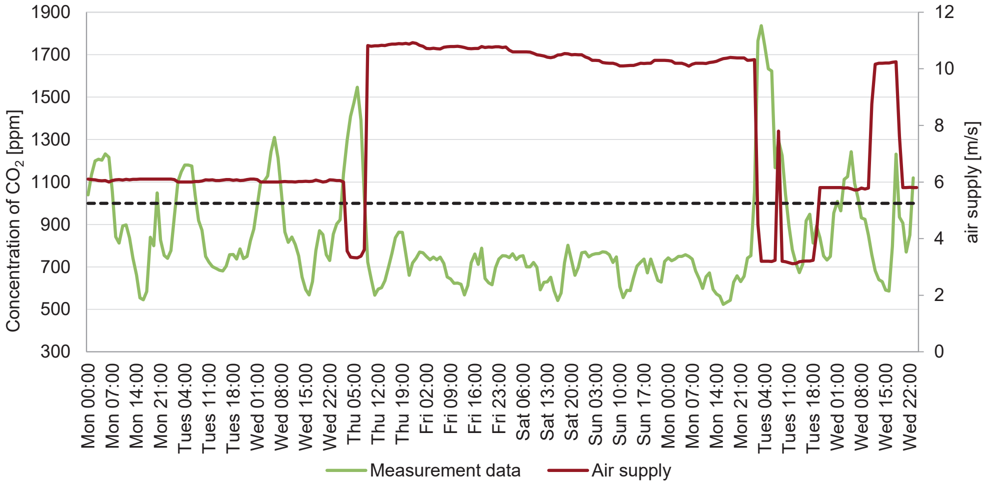

Fig. 5. Ventilation air flow rate and the measured concentration of carbon dioxide in the master bedroom of the passive house; maximum recommended level of 1,000 ppm marked by the dashed line

age of the occupants. According to Gładyszewska-Fiedoruk [9], the maximum night-time concentration of carbon dioxide in the tested bedroom (where the parent and a child slept) was approximately 1,200 to 1,300 ppm; this strongly corresponds with the values measured in the master bedroom of the studied passive house during the periods when the ventilation rate was set at the medium level.

Similar results are shown in the research of Kotol et al. [5] and Bekö et al. [6] where the concentration of carbon dioxide was measured during the night in bedrooms of buildings built in the classic standard, with natural ventilation. In his research, Bekö et al. showed that only 32% out of the five hundred bedrooms which were taken into consideration had proper indoor air quality. In the research performed by Kotol et al. [5] only 34% of the tested bedrooms had a CO_2 level below 1,000 ppm. The reason for this was the low amount of fresh air flowing into the rooms.

In the tested master bedroom, the number of occupants was higher than in a standard master bedroom as it is usually designed for two occupants and the ventilation rate in some cases was too low. When the air flow was higher, the air quality improved showing that the analysed mechanical ventilation system may provide good indoor air quality when properly controlled. Even though the houses in the mentioned research papers by Kotol et al. [5] and Bekö et al. [6] were built in a classic building standard ventilation and the test object described in this paper was built in a passive standard with mechanical ventilation, the same issues concerning contaminant concentration occur. This means that the mechanical ventilation system in the passive house does not always provide better indoor air quality than objects with a natural ventilation system. The key issue is proper control of the ventilation system (with regard to air flow rate) and adaptability to changing conditions.

4. CONTAM simulation results

The influence of occupancy schedules and the effectiveness of ventilation on the contaminant concentration inside the master bedroom of the studied passive house was analysed using the CONTAM software application. In each case, the computer simulations were compared to measurement results as different scenarios were discussed.

4.1. Simulation with minimal ventilation rate

As shown in Fig. 5, when the minimal ventilation rate was turned on, the concentration of carbon dioxide was the highest. Figure 6 shows the results of the CONTAM simulations conducted for the minimal ventilation air flow rate compared to measurement results recorded in the analysed period. Figure 7 presents the results of the CONTAM simulations for the minimal ventilation air flow rate but with the closed walk-in wardrobe.

The figures above show that the highest CO_2 peaks (Thursday from 3 am to 9 am and Tuesday from 2 am until 9 am) were in fact because of the low ventilation rate. However, they also show how occupant behaviour influenced the results. In the first simulation, where the door between the bedroom and wardrobe was open (Fig. 6), the concentration of the contaminant is lower than in the second scenario, when the door to the wardrobe was closed (Fig. 7). During the simulation with the door opened, the maximum calculated CO_2 concentration was around 1,500 ppm, which corresponds to the contaminant peak from the Thursday morning. When the door was closed, the calculated concentration increased up to 1,800 ppm. This level of around 1,800 ppm also corresponds to the CO_2 level during the second contaminant peak that occurred on the second Tuesday between 2 am and 9 am,

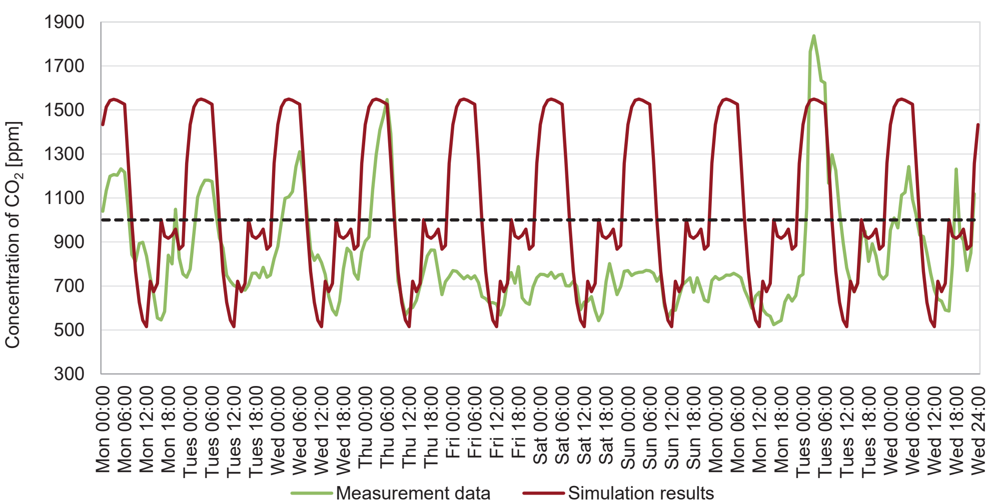

Fig. 6. Carbon dioxide concentration – simulation with the minimal ventilation rate and open door to the walk-in wardrobe; maximum recommended level of 1,000 ppm marked by the dashed line

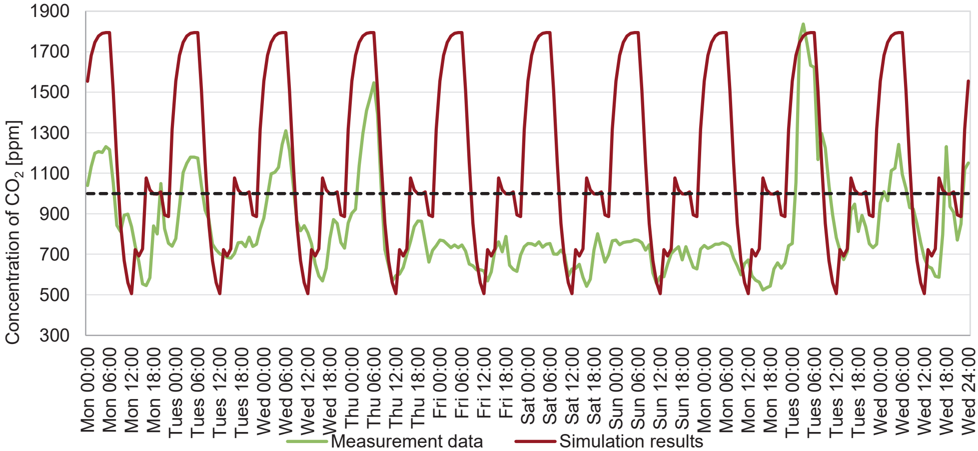

Fig. 7. Carbon dioxide concentration – simulation with the minimal ventilation rate and closed door to the walk-in wardrobe; maximum recommended level of 1,000 ppm marked by the dashed line

meaning that during this period, the occupants slept with closed doors to the bedroom. This shows how contaminant migration within a household may occur and how minor details influence the indoor air quality.

4.2. Simulation with medium ventilation rate

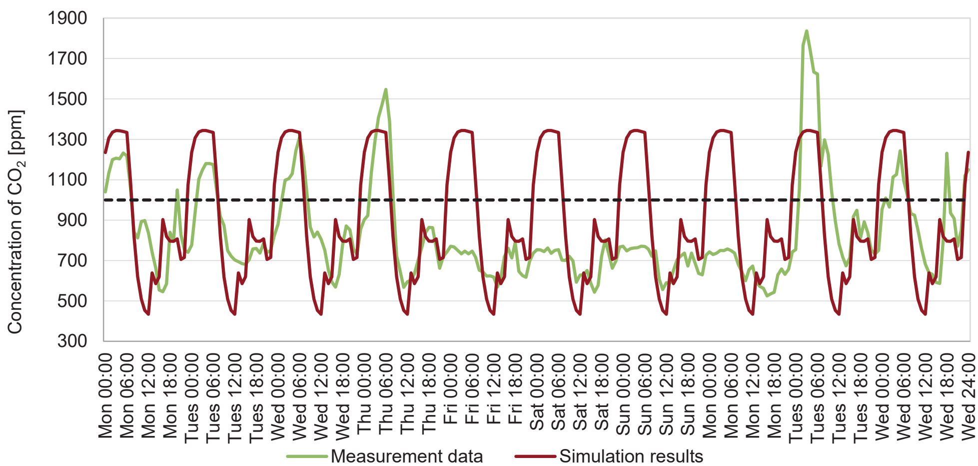

Fig. 8. Carbon dioxide concentration – simulation with the medium ventilation rate and open door to the walk-in wardrobe; maximum recommended level of 1,000 ppm marked by the dashed line

The medium ventilation rate was activated by the occupants between Monday at 12 am and Thursday at 1 am as well as from the second Tuesday at 8 pm until the second Wednesday at 10 am. In the simulation, it was assumed that the door to the wardrobe was open and the door to the hallway was closed (Fig. 8). The simulation results correspond to the measurement data as the peaks of CO_2 are noted in the same time frame. However, in most cases, the maximum concentration in the simulation is higher than real measurements and the minimal calculated CO_2 level is 434 ppm while the minimal level of the contaminant in reality was 524 ppm. Because of this discrepancy, it was decided to perform a simulation in which both of the bedroom doors were open. The results of the simulation are shown in the figure below.

The simulation with both doors open (Fig. 9) corresponds to the measurements in the period when the medium ventilation rate was set. The minimal CO_2 level corresponds to the level of the contaminant from the measurement data.

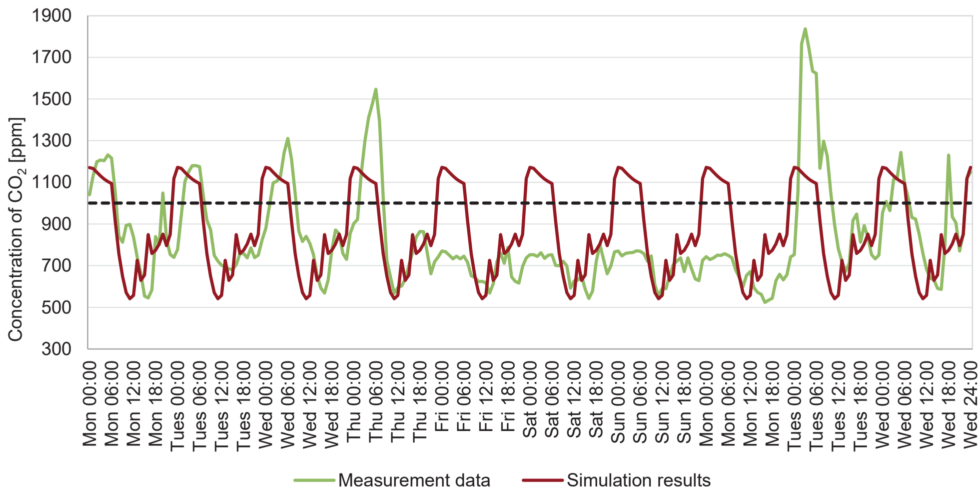

Fig. 9. Carbon dioxide concentration – simulation with the medium ventilation rate and both doors open; maximum recommended level of 1,000 ppm marked by the dashed line

4.3. Simulation with maximum ventilation rate

The maximum ventilation rate was mainly active between Thursday at 9 am until the second Tuesday at 2 am. According to the occupants' statements and analysis of the sensor results, only the female adult and the child slept in the bedroom during this period. The occupation schedule was altered during the simulations with regard to the maximum ventilation rate so as to take this change into account. The first simulation with this ventilation rate was conducted with only the wardrobe door open; this is shown in Fig. 10. However, similar to the situation with the medium ventilation rate, the real contamination level did not correspond with the simulation results, which showed a significantly lower contaminant level. This is why an additional simulation was conducted in which it was assumed that both doors to the bedroom were open. The results of this simulation are shown in Fig. 11. The results from this simulation corresponded better to the real results especially with regard to the minimal CO_2 level.

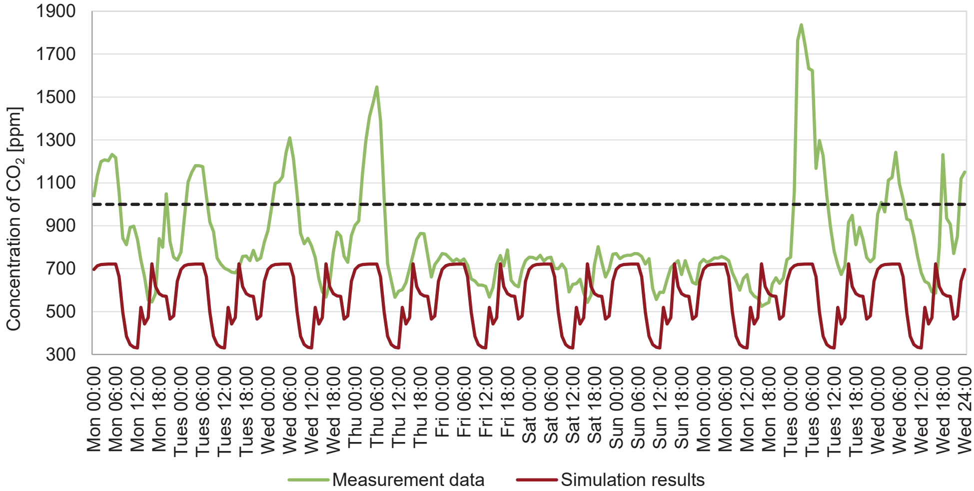

Fig. 10. Carbon dioxide concentration – simulation with the maximum ventilation rate and door to the walk-in wardrobe open; maximum recommended level of 1,000 ppm marked by the dashed line

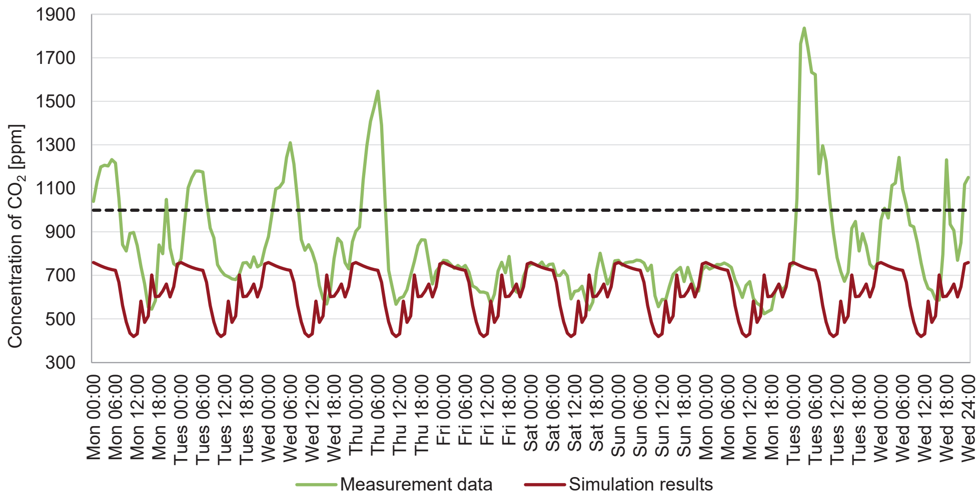

Fig. 11. Carbon dioxide concentration – simulation with the maximum ventilation rate and both doors open; maximum recommended level of 1,000 ppm marked by the dashed line

4.4. Simulation with the occupancy schedule and real ventilation rates.

After the analysis of the different scenarios, a full simulation was conducted that included the occupancy schedule and the real ventilation rates; the results are shown in Fig. 12. This figure shows that it is possible to model the conditions of carbon dioxide concentration inside the analysed bedroom based on the occupancy schedule and the real ventilation rates.

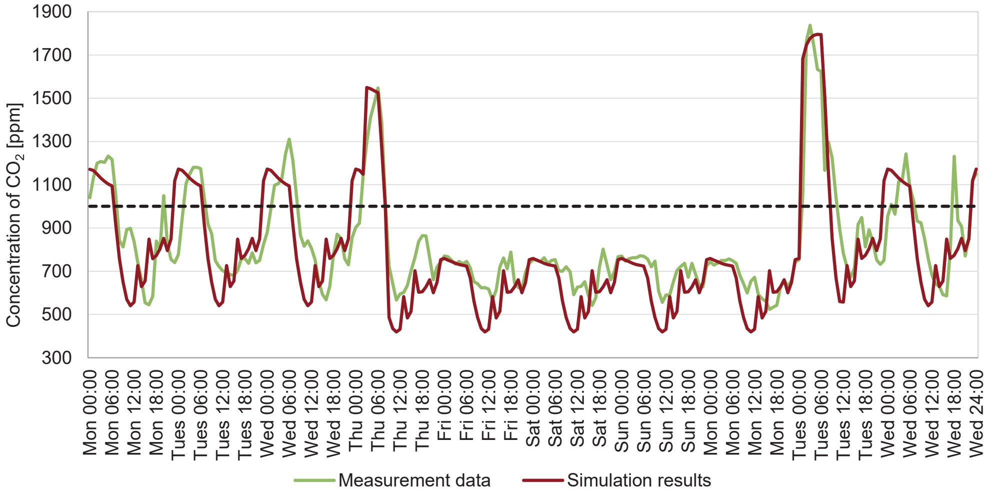

Fig. 12. Carbon dioxide concentration – measurements and the results of simulation with the occupancy schedules and real ventilation rates; maximum recommended level of 1,000 ppm marked by the dashed line

5. Conclusions

In this paper, the results of the measurements and simulation of carbon dioxide concentration as an indicator of the quality of indoor air inside of a master bedroom of the inhabited passive house have been shown. The measurements were performed to determine if the quality of the indoor air of the test object meets the hygienic standards. The aim of the conducted simulation was to determine if it is possible to recreate the conditions of carbon dioxide concentration inside of the analysed bedroom and to what extent.

The measurement results show that the concentration of carbon dioxide in the master bedroom of the analysed passive house mostly remained below 1,000 ppm – the recommended maximum indoor concentration of carbon dioxide that should not be exceeded for hygienic reasons. However, this value was periodically exceeded to a significant degree for episodes usually lasting 7-8 hours, which can be connected to the sleeping patterns of the occupants. These periods were recorded for most of the nights during the test period. The values of maximum concentrations of CO_2 during the night were usually around 1,200 ppm; on one occasion, 1,500 ppm was registered and on another occasion, the registered value was 1,800 ppm.

The maximum concentration of carbon dioxide in the master bedroom of the analysed passive house measured during the periods when ventilation rate was set on the medium level are comparable to the values reported by Gładyszewska-Fiedoruk [9], who analysed the concentration of carbon dioxide within bedrooms of a detached house, built in the classic building standard with natural ventilation. When the air flow rate was higher, the air quality improved showing that the analysed mechanical ventilation system may provide good indoor air quality when properly controlled. Even though the houses in the mentioned research papers by Gładyszewska-Fiedoruk [9], Kotol et al. [5]and Bekö et al. [6] were built in a classic building standard with natural ventilation and the test object described in this paper is built in a passive standard with mechanical ventilation, the same issues concerning contaminant concentration occur. This means that the mechanical ventilation system in the passive object does not always provide better indoor air quality than objects with a natural ventilation system. The key issue is proper control of the ventilation system (air flow rate) and adaptability to changing conditions.

This project has shown that the registered exceedances of the recommended indoor levels of carbon dioxide were associated with the regulation of the mechanical ventilation system implemented by the occupants, who freely changed the ventilation rate according to their will. The occupants reported that the night-time ventilation airflow rate was often lowered to a minimum to eliminate noise; this can be seen in the results of the conducted measurements. This underlines the importance of occupant behaviour and awareness with regard to the control of mechanical ventilation in passive houses.

Due to the nature of passive buildings, during the design phase, special attention should be placed on the fact that the number of people in different rooms and their physical activity can differ strongly from the design values. If the ventilation system does not take into account the actual amount of household members (or potential visitors), it may be insufficient in providing appropriate indoor air quality. The simplest solutions for this problem the possibility of opening the windows to periodically increase the intensity of ventilation (inflow of fresh air) – in passive houses is very limited. A potential solution could be the use of a variable air volume ventilation system (VAV) controlled individually for each room by the level of carbon dioxide. This view is consistent with the results of Batog & Badura's [10] research who recommend applying demand-controlled ventilation using sensory information rather than systems based on designed air exchange rates as the only proper way to provide both good air quality and good energy efficiency of a building. Such systems, however, are much more expensive, which certainly is a barrier to their use in objects such as a detached house.

The results of the conducted CONTAM simulation showed that it is possible to model the conditions with regard to carbon dioxide concentration inside of the analysed bedroom based on the occupancy schedule and the real ventilation rates. The prediction of contaminant concentrations can be used to determine the indoor air quality of a building before it is constructed and occupied or to investigate the impact of various design decisions related to ventilation system design.

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The application of computed tomography in the automotive world – how industrial CT works

Zastosowanie tomografii komputerowej w świecie motoryzacji – jak działa przemysłowa TK

Abstract

This paper shows how industrial computed tomography (CT) works, its benefits and where it can be used in automotive world. As a non-destructive quality control technique (NDT), CT allows not only the measurement and evaluation of external and internal geometry, but is also useful for making reports with a visualisation of an entire component, e.g. a map of shape deviation and internal structural defects.

Keywords: industrial CT, flat beam, cone beam, internal structural defects, dimensional accuracy

Streszczenie

W artykule przedstawiono zasadę działania przemysłowej tomografii komputerowej (TK), jej zalety oraz zastosowanie w branży motoryzacyjnej. Jako nieniszcząca technika kontroli jakości (NDT), TK pozwala nie tylko na pomiar i ocenę geometrii zewnętrznej i wewnętrznej, ale jest również przydatna w sporządzaniu raportu z wizualizacją całej części, np. mapy odchyłek kształtu czy defektów struktury wewnętrznej.

Słowa kluczowe: przemysłowa TK, płaska wiązka, stożkowa wiązka, wady struktury wewnętrznej, dokładność wymiarów

1. Introduction

Technological research and development centres play an extremely important role in the automotive industry during the entire manufacturing process of structural elements starting from the inception of new ideas. The aim of these centres is to design components that can be produced to meet the applicable standards and tests, in accordance with the required quality standards. Usually, the whole process of developing new components takes from three to five years. The stage at which engineers check the quality of the first prototypes and all finished components and products is very important. Then with help comes computed tomography which is very useful machine for testing and assessment of dimensional accuracy and internal structural failures. Industrial computed tomography can also be used in a reverse engineering capacity to scan finished products in order to rebuild the 3D model in CAD software and make improvements; this model can also be used for 3D printing. Finally, after all tests, calculations and modifications of the CAD model and its technical drawing specification, we get a product that meets manufacturer and customer requirements. Figure 1 shows computed tomography – Nikon XT H 225 ST for industrial CT scanning. On the CT table is the final product ready for scanning [1].

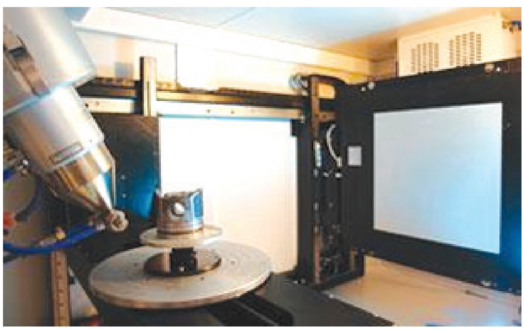

Fig. 1. Computed tomography – Nikon XT H 225 ST [1]

2. Computed tomography – principles

CT – computed tomography is a measuring device that has a wide range of applications in industry despite the fact that people generally think of CT as being a medical tool. The first prototype of computed tomography, the 'EMI schanner', was made in 1968 by G.N. Hounsfield. The name of the technique, the mathematical apparatus and the technological workshop used for generating images and volume elements in a three-dimensional form has changing over time. In 1979, Allan MacLeod Cormack (1924–1998) and Godfrey Newbold Hounsfield (1919–2004), received the Nobel Prize for Medicine for the discovery of computed tomography [2–4]. More about the genesis and principle of operation of each of the five computed tomography generations can be found in references 5 and 6. In the 1980s, industrial applications were found for computed tomography in the form of non-destructive testing (NDT) techniques; it has now become a revolutionary metrology tool for the comparison an evaluation of geometric tolerances and dimensions. This technique allows the measurement of components in both 2D and 3D, but the most important fact is that it allows the mapping of external shapes and the internal structure of the tested component without disassembling it into its individual components for internal measurements [7–11].

Computed tomography is a type of X-ray spectroscopy, it is a diagnostic method that enables the obtaining of layer images of the examined object [2]. Cross sectional images (2D) and 3D reconstructions are created by compiling many projections of flat images of a three-dimensional spatial object, created as a result of X-ray scanning of the tested object in given angular positions [2, 10–15].

There are few common steps to conducting a CT x-ray or a CAT scan. Taking into consideration the purpose of the scan, the radiographer must prepare the subject for scanning, calibrate the system and match the part size and material to an appropriate x-ray source with regard to the level of exposure. The part to be scanned is placed on a rotatory table located between the digital detector panel and the x-ray radiation source. The CT system has to be shut down before the scanning process and exposure to x-rays. As the part rotates through 360 degrees, the x-ray source penetrates through each part of the scanned item. The various densities of the part absorb varying amounts of radiation. The remaining radiation travels to the detector panel, which captures a 2D x-ray image. To obtain a 3D rendering or a 3D model of the scanned part, several hundred to several thousand 2D x-ray images captured while scanning are needed; the next step is to produce a mathematical reconstruction [2, 4, 10–13, 16–19]. For the use of industrial CT systems today, transform methods and a restorative algorithm (based on analytical inversion formulas) are implemented as they are much faster than traditional methods of the reconstruction of CT data sets. This method of reconstruction also allows greatly enhanced image quality and accuracy [19].

Two types of projection systems are most commonly used in industrial CT scanning. One is a system with a flat beam of radiation (see Fig. 2) and the other is with a cone beam (see Fig. 3) [17, 20].

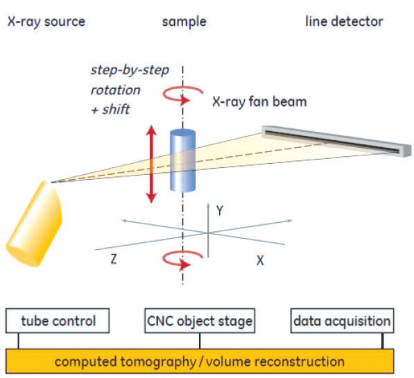

Fig. 2. Scheme of CT with fan beam [17]

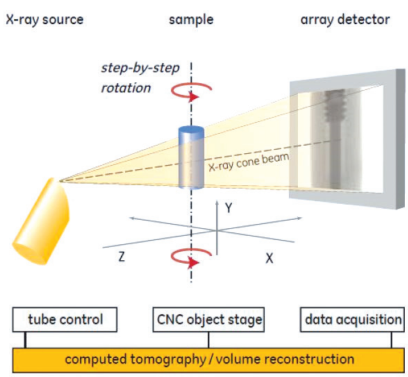

Fig. 3. Scheme of CT with cone beam [17]

3. Benefits of using CT scanning in industrial applications

The main advantage of this technology is the fact that it provides highly accurate testing results without applying any pressure, stress or external forces on the subject being scanned. The following is a brief list of all the major benefits this technology offers:

- non-destructive testing method,
- quantitative density evaluations,
- geometrical representations,
- cross sectional data and 3-dimensional data,
- images are easier to interpret than conventional radiographic data,
- quality control tool for failure investigation and preproduction inspection,
- internal part inspection,
- external part inspection,
- quick and accurate resulting data,
- accessible with the use of outsourced NDT labs,
- saves manufacturing cost (NDT),
- cuts costs and reduces time to production,
- accurate and precise means of measurement,
- enables different types of analysis with one CT dataset,
- non-invasive and non-intrusive method of inspection,
- research and development tool,
- 3D visual representation of part interior.

The following applications of computed tomography within the automotive industry have been identified:

- automotive design and styling,
- automotive component inspection;
  - fault detection and failure analysis,
  - dimensional measurement of internal components,
  - advanced material research;
- assembly inspection of complex mechanisms,
- part-to-CAD comparison (Figs. 4 and 8),
- digital archiving of models.

Fig. 4. Real part scan (STL) to CAD model comparison – plastic part of fan

In the automotive industry, computed tomography is mostly used for quality control, failure analysis and material research. This technology serves as an efficient tool for providing valuable information in any situation in which the internal structure matters. Below is brief list showing the wide range of applications:

- electrical connectors,
- injection nozzles,
- sensors (e.g. Lambda sensors),
- LED light pipes,
- small high-pressure die cast parts, casting inspection (Fig. 5),
- DPF (diesel particulate filters),
- turbine blades and housing inspection (Fig. 6),
- plastic injection moulding (Fig. 7, 8);
  - complex plastic components (e.g. fan),
  - soft, translucent materials where tactile or optical investigation is not option,
  - ultrasonic welding of plastic parts;
- research;
  - material verification and analysis (e.g. structure, porosity, defects) (Fig. 5, 6, 7),
- packaging (Fig. 7).


Fig. 5. Casting inspection [1]

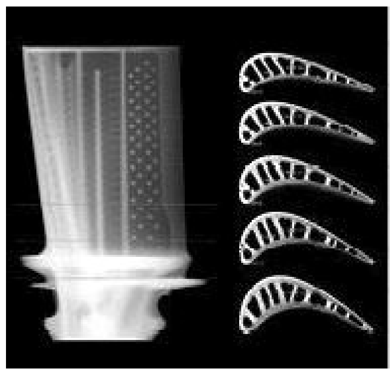
Fig. 6. Turbine blades inspection [1]


Fig. 7. Fan in assembly of cooling module

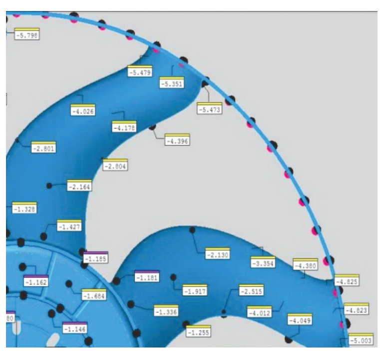
Fig. 8. Fan dimensional accuracy, Part-to-CAD comparison

4. Conclusion

The application of industrial computed tomography in the automotive industry is a very useful and optimal tool for the verification and evaluation of dimensional accuracy, shape and internal structural defects of components. In order to meet customer requirements, tomography is an excellent technique at all stages of product development in order to check quality and make improvements.

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Computed tomography as a quality control technique in the 3D modelling of injection-moulded car system components

Tomografia komputerowa jako technika kontroli jakości w procesie modelowania 3D elementów samochodowych formowanych wtryskowo

Abstract

This paper presents the sophisticated capabilities of industrial computed tomography (CT) in the development and 3D modelling process of new car system components. Usually, the process of the development of new car components takes three to five years. At each development process stage, quality control is crucial to catch all internal and external defects. This is particularly important with regard to components made using an injection-moulding process. Computed tomography as a non-destructive testing method is an excellent tool for controlling and improving both the manufacturing process and the 3D modelling of tested components. All analyses performed with use of CT are essential for meeting customer requirements. This paper shows how industrial computed tomography can control the quality of the car components development process.

Keywords: industrial CT, CAD 3D model, STL, quality control, product development process

Streszczenie

Praca przedstawia zaawansowane możliwości przemysłowej tomografii komputerowej (TK) w rozwoju i procesie modelowania 3D nowych elementów samochodowych. Zazwyczaj proces powstawania części nowego samochodu trwa od trzech do pięciu lat. Na każdym etapie rozwoju produktu kontrola jakości jest kluczowa w wychwyceniu zarówno wewnętrznych jak i zewnętrznych wad. Jest to niezwykle ważne zwłaszcza dla elementów wywarzanych w procesie wtrysku. Tomografia komputerowa jako nieniszcząca metoda badawcza jest wspaniałym narzędziem do kontroli oraz ulepszania procesu wytwarzania i jednocześnie ulepszania modelu 3D badanego elementu. Wszystkie analizy wykonane przy pomocy TK są niezbędne, aby sprostać wymaganiom klienta. Artykuł pokazuje zastosowanie przemysłowej tomografii komputerowej jako narzędzia do kontroli jakości w procesie rozwoju elementów samochodowych.

Słowa kluczowe: przemysłowa TK, model 3D CAD, STL, kontrola jakości, proces rozwoju produktu

1. Introduction

The main aim of engineers in technological research and development centres is to design components that can be produced in accordance with the relevant quality requirements whilst meeting the applicable standards and tests. Computed tomography is a very useful machine for the testing and assessment of dimensional accuracy and structural failures. The industrial application of CT is also used in reverse engineering to scan finished products in order to rebuild a 3D model in CAD software and make improvements. We can also use this model for 3D printing. Finally, after all simulations, calculations and modifications of the CAD model, tests on real prototype part, and corrections on its technical drawing specification, a product that meets all the requirements is produced.

Fig. 1. Industrial CT Nikon XT H 225 [1]

2. The design process of plastic components

2.1. The principles of injection moulding

It has to be mentioned that there are several processes for moulding plastic to transform it into useable shapes. Plastic car elements are manufactured using various injection technologies. Within the automotive industry, both interior and exterior injection-moulded plastic elements are produced, for example: engine covers, handles, shields, fans, shrouds, tanks, dashboard, seats, doors, brackets, clips.

While the injection moulding is one of the most widely used processes, other processes include:

- reaction injection moulding,
- rotational moulding,

- blow moulding,
- compression moulding,
- extrusion moulding,
- rotocasting,
- transfer moulding,
- thermoforming,
- vacuum-forming,
- blown film extrusion.

A good design is of great value for any manufactured product, but for plastics it is absolutely essential. They creep and shrink as time passes; their properties change over the temperature range of everyday life; they may be affected by common household and industrial materials.

A well-designed object combines concept with embodiment (Fig. 2). Unless the two are considered together, the result is an article that either cannot be made economically or fails in use. This is particularly important consideration for plastics. It is crucial to choose the right material for the task. When this is achieved, it is equally important to adapt the details of the design to suit the characteristics of the material and the limitations of the production process [4].

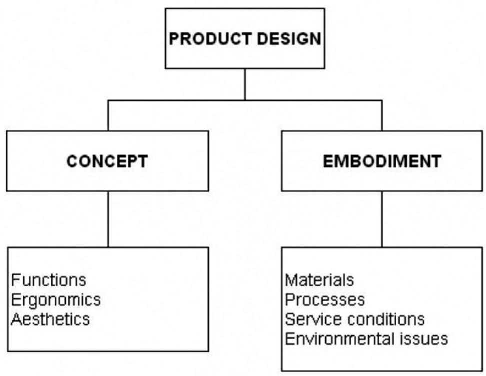

Fig. 2. Design considerations [4]

The complexity of plastic car elements is increasing, while simultaneously, there is a need to minimise development times. In order to meet these requirements, a high degree of quality assurance is needed [5, 6]. The product development process is laborious and long-lasting and must always be improved in conjunction with the development process for moulds. The engineering tasks involved in injection moulding are: the design of the geometry of parts and moulds; the machining and polishing of cavity/core surfaces and cooling lines; the assembly of plates, pins and mould bases; the performing of prototype tests with appropriate choices of material and processing parameters [7]. Therefore, there are strict rules and recommendations for product and mould design. Parts to be injection moulded must be very carefully designed to facilitate the moulding process. It is crucial to adhere to these rules to maintain a high quality of the final products.

There are a few very important points that must be taken into account during the design of both the part and the mould. This narrow range of design rules facilitates the versatility of injection use with regard to:

- the material used for the part,
- the desired shape and features of the part,
- the material of the mould,
- the properties of the moulding machine.

Industrial CAD designers or engineers design the products and the moulds, but the moulds are produced by a mould maker or a toolmaker. Moulds are made usually from metal, either steel or aluminium, and are precision-machined to form the features of the desired part. Figure 3 shows an injection moulding machine [8].

Keeping in mind the material shrinkage, all designing rules need to be applied in order to obtain a plastic part with the specified tolerances. Meeting all the requirements of the entire development and manufacturing process are difficult tasks for the engineers. To read more about mould design and injection moulding, refer to [9–13].

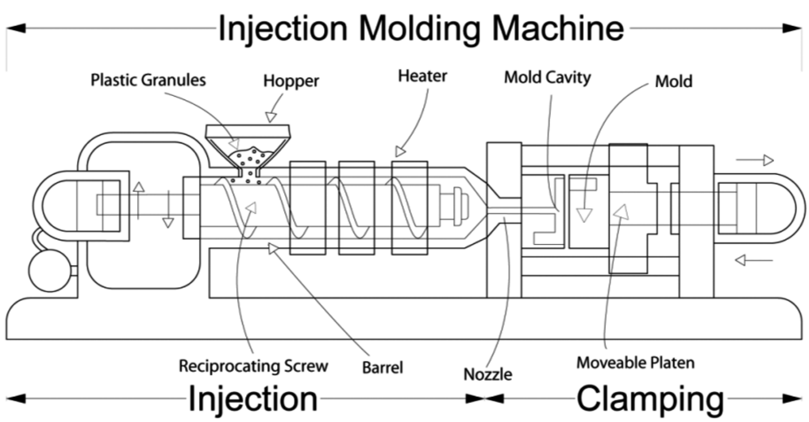

Fig. 3. Injection moulding machine [8]

2.2. Development process

Basically, there are three main stages of the development and manufacturing process: mock-up, prototype, series. In projects, there are more stages according to, inter alia, purchasing, management. However, we are concerned only with the basics of the development process in this paper. Firstly, research and development engineers have to check car packaging (car environment) and calculate stack up tolerances. The designing process then starts for each part and the whole assembly with the desired specified tolerances. The first attempts at trying new ideas are usually based on older versions of the products and developed according to requirements and updated car packaging. In the designing process, there are a few steps which are repeated until the final part is obtained. These steps are: designing the part according to the packaging and designing rules; CAE simulations with test specification in accordance with customer requirements; testing of the part; calculations and changes to the design and tolerances. Tests on an actual part can also be performed on a 3D printed part if the kind of test allows that, for example, an acoustic test of a fan system, some vibration tests. These processes can be repeated many times if needed. At each step, the engineer has to calculate stack up tolerances and prepare technical drawings with specified tolerances taking into account all the design rules of the plastic part and moulds.

To ensure high quality products, very precise measurement techniques are needed to control the quality of the product at each development and production stage. Then with help comes computed tomography. Computed tomography is used to perform fast and precise measurements of the product and compare it with the CAD model. It is vital to check all specified tolerances on the technical drawing. As previously mentioned, plastics have an unpredictable nature and moulds need to be perfectly designed to achieve the final part after shrinkage as required by the drawing. CT software provides the option to compare a CT scan of the product with the CAD model in order to map shape deviation, check for structural defects (internal and external) and prepare a dimensional report GD&T. That metrology CT process refers to Fig. 4.

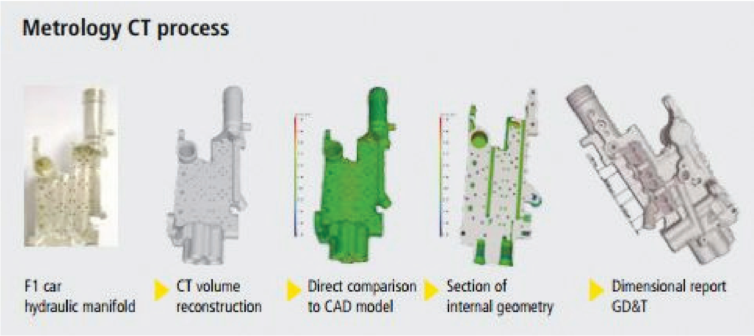

Fig. 4. Metrology CT process of product inspection [1]

3. Industrial Computed Tomography

In the 1980s, computed tomography found its application in industry as a non-destructive testing (NDT) technique. Today, it has become a crucial metrology tool for the assessment and comparison of geometric tolerances and dimensions. Industrial CT as an NDT technique allows products to be scanned without disassembling them into their component parts. This technique also provides highly accurate results of external shapes and internal structures without applying any external forces, pressure or stress. It allows parts to be measured in both 2D and 3D. When used as a research and development tool, as is the case in this paper, it is very important that CT is applied for quality control, the investigation of failures and for preproduction inspection. These strategies can help to reduce manufacturing costs, can reduce both the costs and time of production, and can provide help to designers and engineers with regard to calculations and improvements to the design of both the part and the mould. Images are easy to interpret and there is also the option to map shape deviations and measurements of structural defects; this is very useful in preparing metrological reports of scanned parts [14, 15, 16, 17, 18, 19].

There are two variants of projection systems commonly used in industrial CT scanning. One is a system with a cone beam (see Fig. 5a) and the other is with a flat beam (see Fig. 5b).

a) b)

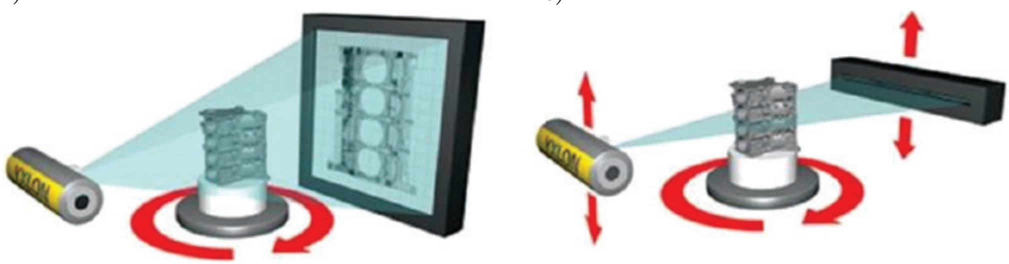

Fig. 5. Scheme of CT with a) cone beam and b) flat beam [20]

3.1. Benefits of using CT scanning in automotive applications

The application of industrial computed tomography at each product development stage in the automotive industry:

- design and styling of car system components
- small and large inspection potential with regard to:
  - fault detection and failure analysis
  - dimensional measurement of internal and external structures
  - advanced material research, for example, plastic parts, small castings
- internal inspection of components: dimensional measurement
- assembly inspection of complex mechanisms
- part-to-CAD comparison
- digital archiving of models
- reverse engineering
- 3d printing
- improvements of CAD model and production (moulding and casting)

4. Case study: plastic parts – fan system shroud and fan

Many plastic components are found in car cooling systems. This section of the paper focusses on the fan system, which includes one of the most complicated plastic parts in its assembly. The system includes a shroud which takes the main stresses and loads from the motor and fan, and the fan itself with each blade having a complex shape. Critical areas of the assembly are the mounting points; it is at these points where the worst simulation results occur. Both the simulation and tests on actual parts are made in accordance with the recommended specification denoted on the customer requirements document. During the vibration test on the actual parts (prototype assembly of cooling module), signs of wear appear. Vibration tests typically show the same main signs of wear as the simulations, but there are exceptions to this. Usually, the vibration test also shows that such wear is caused by material defects or due to the parts not being within geometrical tolerances. Computed tomography can be a useful tool in such circumstances. Prototypes are scanned in order to find the cause of defects and determine their type. CT scanning is fast and very effective for the assessment of all kinds of internal and external defect. Thanks to CT optimal scanning volume there is no need to cut parts into smaller pieces to make a scan. The entire part can be placed on the CT table to scan and analyse everything which is not visible to the naked eye. Computed tomography has dedicated software with options to create, after measurements, map of shape deviations and visualisation report.

4.1. Shroud – internal and external defects

Fan system – shroud specifications:

- *development stage:* prototype,
- *material:* PP-GF40,
- *simulation test – cooling module:* performed after each CAD model design modification, the highest stresses shows on the brushless motor mounting areas but are not critical
- *test on the real parts – cooling module:* vibration,
- *problem:* cracks on the shroud crown on the brushless motor mounting points area after vibration test – Fig. 6.

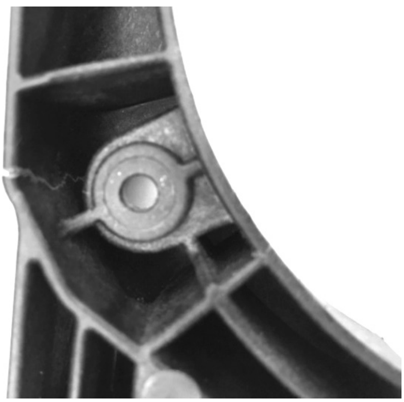

Fig. 6. Mounting area on the shroud crown after vibration test – visible crack

A vibration test was carried out on one of the prototype versions of the cooling module. The test caused cracking of the shroud crown on the brushless motor mounting area. The shroud was scanned by an Industrial CT Nikon XT H 225; it shows that there were a lot of internal material defects (Figs. 7 and 8). After analysing all the defects formed during the vibration test, the shroud was remodelled. Figure 9 shows the two models overlapped – one before changing the design (the part subjected to the vibration test) and the other after remodelling. Changes to the shroud design were accepted and manufactured as a new prototype version. The new part was tested successfully on a cooling module vibration test. To eliminate internal defects, not only was the shroud design changed, the mould and injection moulding process was also improved. Internal defects visible on the CT scan as material discontinuities cause weakening and cracking of that area. Changes to the design of both the part and the mould were crucial in improving the effectiveness of the injection moulding process.

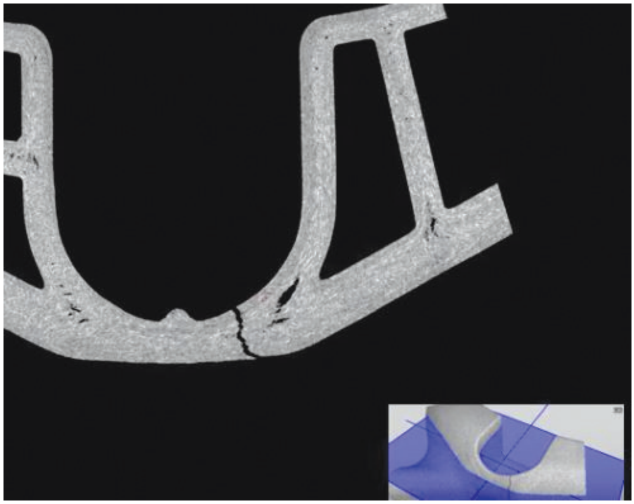

Fig. 7. Mounting area on the shroud crown after vibration test – visible crack on the CT scan and material discontinuities

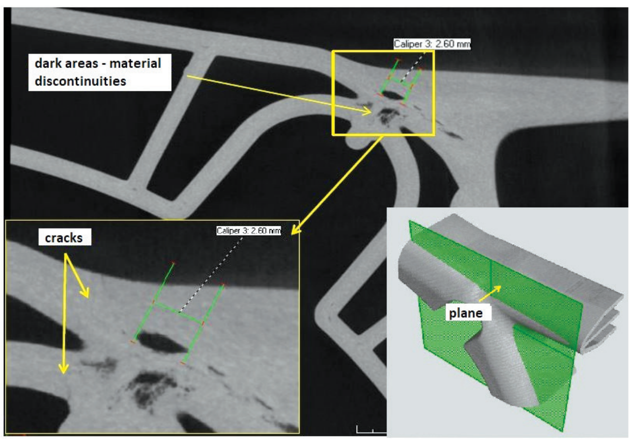

Fig. 8. Mounting area on the shroud crown after vibration test – material defects visible on the CT scan

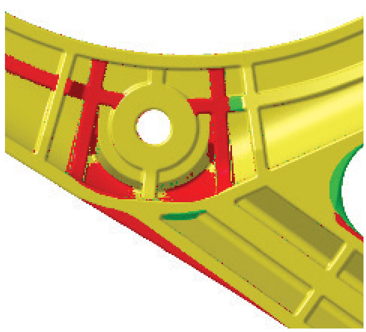

Fig. 9. Two overlapped CAD models of shroud – red indicates new added areas, green indicates old corrected areas, yellow indicates no change

4.2. Fan – shape defects

Fan system – fan specifications:

- *development stage:* prototype
- *material:* PA66-GF30
- *simulation test – cooling module:* performed after each CAD model design modification
- *test on the actual parts – cooling module:* vibration, acoustic, air flow
- *problem:*
  - test results revealed problem with balance and when balancing clip was mounted, it showed that the thickness of the blades was not within tolerance
  - during vibration test fan rub against the shroud
- *CT scanning:* after the vibration test, the fan was scanned and that STL scan model was overlapped with its CAD model. This shows that there were a lot of shape defects and shape deviations were not within tolerance. During rotation, the fan rub against the shroud causing defects and compromising efficiency. To improve the fan injection moulding process small corrections were made on the CAD fan model. The moulds and moulding process were corrected in accordance with the improved CAD model. All procedures were repeated a couple of times until the final part was within tolerance. Figure 10 presents the CAD model of the scanned fan and a map of shape deviations is presented in Fig. 11.

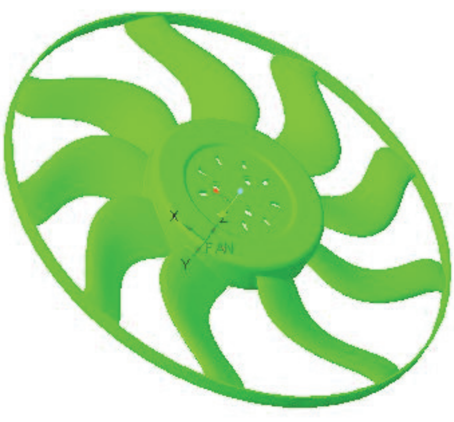

Fig. 10. CAD fan model

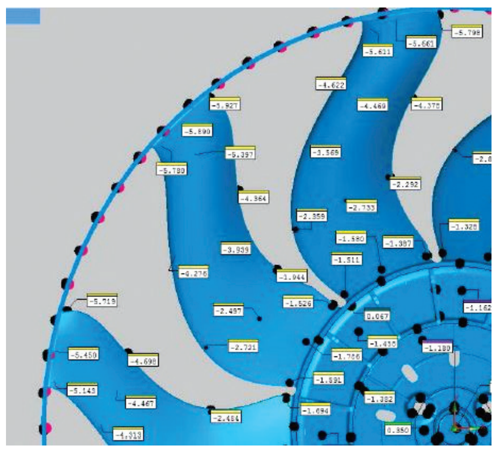

Fig. 11. Map of shape deviations – CAD model and scanned actual part overlapped

5. Conclusion

The application of industrial computed tomography to control the quality of car components at each development stage is needed. The main advantage of this method is the fact that the scan is performed without applying any external forces, pressure or stress. Thanks to the possibility it offers to investigate internal structures and shape failures in a non-destructive manner, it also functions as a tool for preproduction inspection. Moreover, we can cut costs and reduce production time by analysing CT scans of manufactured prototypes before and after testing in order to introduce improvements on time. Thanks to CT, it is much easier to check all main metrological aspects like internal material discontinuities, shape defects or dimension accuracy. Engineers can made a map of shape deviations, compare test reports with simulations and performed Part-to CAD comparison. After analyzing all these results they introduce improvements both on the product and on the mould in order to meet manufacturer and customer requirements. Software that is dedicated to CT has many excellent tool options for all kind measurements and also helps with the preparation of graphic reports including measurements and defect analysis. To summarise, industrial computed tomography is an irreplaceable device in automotive research and development centres as a quality control technique for the comparison and evaluation of geometric tolerances and dimensions in 2D and 3D.

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