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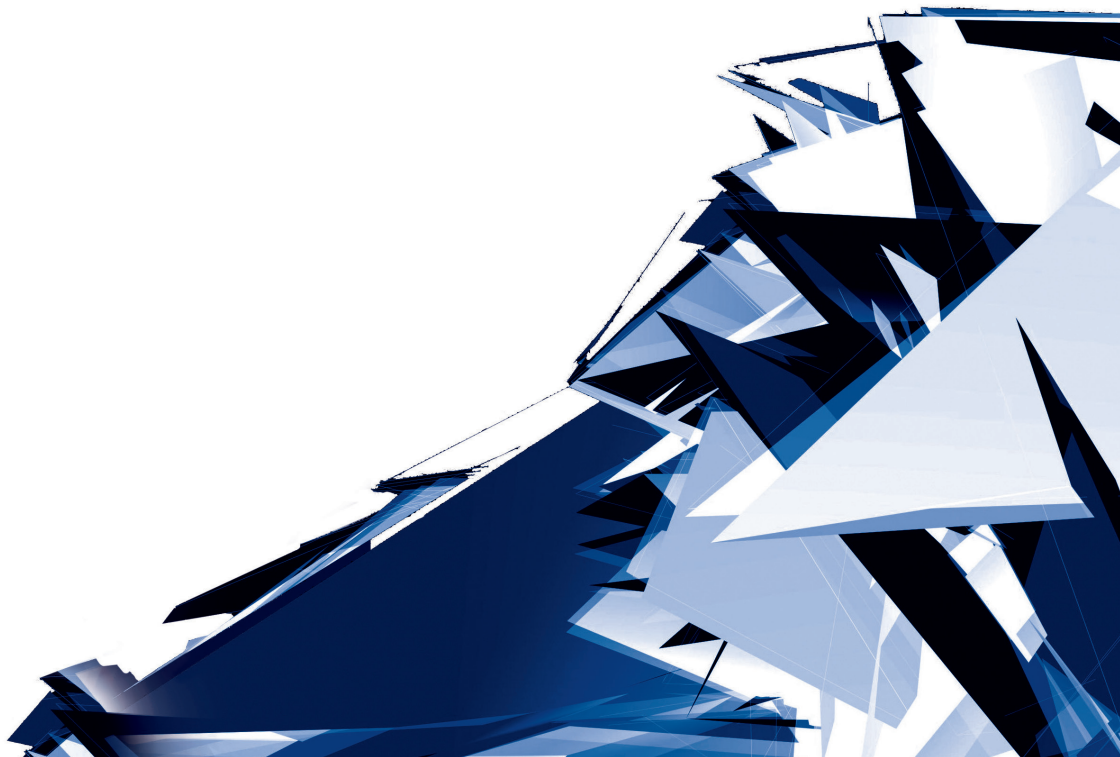

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Post-war modernist architecture in Poland as part of the European heritage of twentieth-century concrete-based architecture

Architektura powojennego modernizmu w Polsce jako część europejskiego dziedzictwa XX-wiecznej architektury betonowej

Abstract

The architectural heritage of post-war modernism in Poland is often named a "dissonant" or "unwanted heritage". Its evaluation and interpretation is often ambiguous, whereas the social reception, in spite of the growing common awareness of the matter, very diversified. A proper assessment of the phenomenon requires analysis against the background of twentieth-century European architecture. The InnovaConcrete project is comprised of multidisciplinary studies on strategies for the preservation of concrete-based heritage which provide for identification of the most valuable assets in Europe. The aim of this paper is to place the local Polish cultural heritage of twentieth-century architecture against the broad context of global and universal values and to present the methodology of the research.

Keywords: concrete-based architecture, post-war modernism, socialist modernism, conservation, 20th century heritage

Streszczenie

Architektoniczne dziedzictwo powojennego modernizmu w Polsce często bywa określane jako "kłopotliwe" bądź "niechciane dziedzictwo". Jego ocena i interpretacja są niejednoznaczne, a społeczna recepcja, pomimo rosnącej powszechnej świadomości, bardzo zróżnicowana. Właściwa ocena zjawiska wymaga analizy na tle europejskiej architektury XX wieku. Projekt InnovaConcrete obejmuje multidyscyplinarne badania nad strategiami zachowania dziedzictwa architektury betonowej, które przewidują indentyfikację najbardziej wartościowych obiektów w Europie. Celem niniejszego artykułu jest umiejscowienie lokalnego dziedzictwa kulturowego architektury XX-wieku w szerokim kontekście wartości globalnych i uniwersalnych oraz prezentacja metodologii badań.

Słowa kluczowe: architektura betonowa, powojenny modernizm, socmodernizm, konserwacja, dziedzictwo XX wieku

1. Introduction

Professor Andrzej Basista described the architecture of the period of the Polish People's Republic as 'concrete heritage'[1]. The twentieth century is sometimes called the century of the 'triumph of silicon, the atom and concrete'. Concrete, a construction material that has been known since ancient times, combined with steel reinforcement, became a material fit for a new century. Reinforced concrete has not only opened a broad spectrum of new possibilities to architects and structural engineers in the shaping of architectural spaces but has also become somewhat of a synonym for modernity. Is the Polish 'concrete heritage' of post-war modernism limited to the unwanted relics of a past period and a reflection of foreign ideas that was not always successful? To what degree does the negligence of recent decades affect the assessment of the heritage of Polish architecture from the period of the Polish People's Republic? When answering these questions, it would be appropriate to consider the architecture of Polish post-war modernism in the broader context of European cultural heritage, as well as currently ongoing studies – both theoretical and those that directly touch on the subject matter of conservation. The motivation for the discussion presented in this article was studies performed as a part of an international multidisciplinary project concerning innovative methods of protecting and conserving concrete architectural heritage.

2. Modern architecture in the Polish People's Republic

It is not possible to confine the history of Polish architecture of the years 1945–1989 to merely a single generalising term by labelling it 'the architecture of the communist period'. A. Basista pointed out that this term is broadly (and mistakenly) associated with the socialist realism of the Stalinist era [1, p. 19]. Subsequent scholars (including Jerzy Hryniewiecki, Tadeusz P. Szafer and Maciej Czarnecki) noted a much a greater diversification of the conditions of architecture in the latter periods of the history of the People's Republic of Poland [16, 4]. In the context of the discussion featured in this article, of particular significance are the periods in which modernist thought dominated domestic architecture.

After the official rejection of the doctrine of socialist realism in 1956, the authorities of the PRL "consider expanding this abbreviation as most non-Polish readers will not know this" saw modernist architecture as a tool for building a new identity for society, as well as an opportunity to bridge the gap that separated the country from the capitalist west. Architects were given the possibility of confronting the achievements of designers from the west with their own works. Successes in this field convinced the authorities that this was the right course for architectural policy [3, p. 66]. One example of this is one of the most significant and most prestigious projects of the 1970s – the Warsaw Central railway station, designed by Arseniusz Romanowicz and Piotr Szymaniak and built in the years 1972–1975. The British press of the time hailed it as a model in terms of the design of such buildings. Werner Huber compared it to other railway stations of capital cities the train stations in Brno and the Paris Montparnasse

Fig. 1. Zarzuela's Hippodrome in Madrid [by author]

station, highlighting the advantage of the Warsaw station. He wrote that the Central Railway Station was a true icon of Poland's capital [10, p. 208].

The conversion of the architecture of the PRL to modernism coincided with the second half of the 1950s, when reinforced concrete shell structural systems were gaining popularity. After the times of the pioneers of these types of structures, such as Eduardo Torroja, Pierluigi Nervi or, in later years, Felix Candela, they became widely used solutions. Their high structural performance, the freedom of their visual form, as well as associations with the abstract art of the turn of the 1940s and the 1950s caused shell structures to become all but a synonym for modernity. At the same time, it was one of the final moments of an international approach to the use of concrete in architecture and a common language of architectural forms in different states. Shell structures were being built from Brazil and Mexico, through Spain and the Soviet Union, all the way to Japan. Along with the revision of modernist doctrines in the 1960s, the discussion shifted towards 'national concrete', while architecture pursued individual, local qualities instead of common values [7, p. 103].

The shell structure fashion did not go unnoticed in Poland, as proven by articles in the daily and professional press from the start of the 1960s. They described individual new projects [2, 12] and explained the general principles of the design of structural systems of this type [21].

Before the complex of the Warsaw Central train station was built, Romanowicz and Szymaniak designed cross-city line railway stations in the capital. The first proposals of four new stations were developed as early as 1954–1955 and assumed the construction of concrete, shell-type structures, each of which was to be adapted to the local context and

was designed to be different from the others. Construction work began in 1962 and was completed in 1963. During this time, the shape of each building changed, but their general principles were preserved; this made it possible to acknowledge them as one of the most interesting manifestations of modernity in Polish post-war architecture even after almost half a century had passed.

3. The InnovaConcrete project in Poland

The individual character of innovative forms, combined with the position of representing a broad trend, caused Warsaw's Cross-City Line stations to become included in the InnovaConcrete – Innovative materials and techniques for the conservation of the twentieth century concrete-based heritage' project [24]. The goal of the project, which was planned for the years 2018–2020, is the valorisation of the heritage of twentieth-century concrete architecture in Europe, the development of innovative methods of its protection and raising public awareness of its value.

The varied character of the activities outlined in the project and the partners comprising the project consortium required a precise division of duties. These include the following closely related fields: analysis of the state of the preservation of selected structures, including on-site and laboratory studies; the development of innovative methods of securing concrete surfaces; the testing of the methods on individual structures. Furthermore, historical and socio-economic studies are conducted simultaneously throughout the entirety of the project; these are aimed at the valorisation and identification of the potential of twentieth-century concrete architecture, as well as raising public awareness of its significance.

All of the studies are conducted on a group of seven selected structures representing different ways of using concrete in architecture and spatial forms (open-air sculptures, monuments) as well as various periods of construction. These are, in order:

- the Centennial Hall in Wrocław (M. Berg, 1911–1913);
- the monuments in Torricella Peligna – the 'Angel' and the 'Tower' (N. Lucci, 1922; W. Sibona, 1950–1961);
- Zarzuela Hippodrome in Madrid (E. Torroja, 1934–1941);
- Eduardo Torroja Institute for Construction Sciences in Madrid (E. Torroja, 1951);
- Cross-City Line railway stations in Warsaw (A. Romanowicz, P. Szymaniak, 1954–1963);
- the remembrance site at Fort IX in Kaunas (A. Ambraziunas, V. Velius, 1984);
- the Elogio del Horizonte sculpture in Gijon (E. Chilida, 1989).

Whilst the selection of the Centennial Hall, a building placed on the UNESCO World Heritage Sites List in 2006, should not raise any doubts [9], the decision to include Warsaw's Cross-City Line railway stations does require a certain degree of explanation. The candidacy of the projects by Romanowicz and Szymaniak was selected from several proposals of post-war concrete architecture in Poland (other structures that were considered for selection included the furniture factory in Wyszków, 'Okrąglak' Poznań Department Store, the apartment blocks at Plac Grunwaldzki in Wrocław, the 'Bunkier Sztuki' art gallery

Fig. 2. Reinforced concrete canopy at the Warsaw Śródmieście WKD railway station [by author]

in Krakow and the Silesian Scientific Institute in Katowice). The choice was motivated by, among other things, the fact that the complex of stations (treated as a whole) constitutes a representation of concrete shell structures, which became a synonym for modernity in Eastern Bloc countries after the 1960s.

From the five shell structures placed in the four stations in Warsaw, one was chosen for the performing of on-site studies – the WKD Śródmieście station. As with the others, this station was built in the years 1962–1963. The trackway, the platforms and the ticket booths were placed below street level. From the perspective of the street, the only visible elements were the downward-leading stairs covered by reinforced concrete roofs (one set of roofed stairs was located in the western part of the platform, while another was placed in the eastern part) [18]. The shape of the reinforced concrete shell structures on top of the WKD Śródmieście station was an original solution. Contrary to other station pavilions, its architects and structural engineers did not use typical straight or quadric surfaces, instead aiming for freely-shaped forms. Thanks to this, completely unique surfaces with organic shapes and a subtly curved surface were formed. Romanowicz's former co-workers mentioned that some of the solutions were designed on-site, during construction. This stance corresponds to F. Candela's principles, who mentioned that despite its apparently strictly scientific character, the design of these types of structural systems must take into account a certain degree of imperfection in workmanship and the calculations themselves. Because of this, the intuition of the architect is necessary; this is closer to philosophy or artistic instinct than pure mathematics [19, p. 274].

4. List of European concrete heritage – initial selection objectives versus their execution

As a part of the activities intended to raise public awareness of the significance of twentieth-century concrete architecture specified in the project by Thomas Harboe (ICOMOS), the Committee endeavoured to make a list of the most important structures.

The initial list, prepared by Susane Landrove and DOCOMOMO Iberico, from which 100 structures were to be ultimately chosen, covered 208 structures. They included both leading works of global architecture (The Unite d'Habitation in Marseilles by Le Corbusier), as well as projects that were relatively poorly studied and discussed (a gas station in Ljubljana by Milan Mihelic), and elements which, due to their strictly technical, infrastructural character, are often ignored by architecture historians (acoustic screens on Malta by the Royal Engineers). It should be stressed that the selection covered only the architectural heritage of European Union member states. Although the adoption of this criterion appears indisputable in light of the assumptions of the entire InnovaConcrete project and the Horizon 2020 framework programme, it has obviously affected the value of the study material. This caused the elimination of structures of such significance like the Goetheanum in Basel (Switzerland), the 'New Belgrade' district in Belgrade (Serbia), the spomenik in Krusevo (Macedonia) and the outstanding projects of Russia and Ukraine, which represented late modernism and constructivism, respectively (e.g. Saint Petersburg's residential towers and the Derzhprom office building in Kharkiv).

Among Polish structures that were placed on the list, there is the previously mentioned Centennial Hall and the market hall in Wrocław (R. Pluddemann, H. Kuster, 1906–1908), the 'Runotex' plush and velvet factory in Kalisz (S. Sikorski, J. Główczewski, W. Zalewski, 1962), the Silesian Scientific Institute in Katowice (S. Kwaśniewicz, 1972–1977) and the Bunkier Sztuki art gallery in Krakow (K. Tołłoczko-Różyska, 1959–1965). The Cross-City Line railway stations in Warsaw, as a complex of structures instead of a single building, were not placed on the list.

Each of the entities working on the list (ICOMOS, CSIC, DOCOMOMO, UŁ) had 100 votes at its disposal, with constraints set in place stating that at least one structure had to be selected from each country. Furthermore, in accordance with the principle of balance (and therefore abandoning scholarly objectivism to a degree), it was decided that each country should be represented by no more than 5 buildings. The key criteria adopted for the evaluation of individual buildings were:

- a structural system based on the use of concrete as the primary construction material and highlighting it in the form of the building;
- the representation of different types of concrete use (monolithic concrete, reinforced concrete, ferro-cement, sprayed concrete, aggregate concrete, concrete finishes on the facade);
- the representation of different types of construction method (concrete cast on-site, on-site prefabrication, off-site prefabrication, concrete block structure);
- the representation of different types of structural systems (e.g. shell structures, concrete frames, domes, arches/parabolic arches, systems based on load-bearing walls);
- the representation of various forms of use;
- the representation of individual countries.

A full set of four votes and an undisputed place on the '100 list' was given to Wrocław's Centennial Hall. Three votes were given to the market hall in Wrocław and the building of the Silesian Scientific Institute. The presence of projects by M. Berg on the list is, however, conditioned by the decision to mandatorily include (or disqualify) buildings that constitute the subject of the project and are mentioned in the previous paragraphs. It can therefore turn out that Polish concrete architecture will be represented by R. Pluddemann's hall and the currently ruined building by S. Kwaśniewicz. This situation begs a series of questions regarding the method adopted in the process of preparing the list.

The arbitrary manner of the selection appears unavoidable in a situation when it is necessary to confine a century of the history of concrete architecture to a mere 100 representative cases. Similarly, it is inappropriate to eliminate the constraint that necessitates the selection of at least one building from each EU member state (the upper limit of five buildings is, however, questionable). At the same time, concerning the fact that practically all of the buildings represent different phases of the development of modernism, perhaps it would be justified to highlight the aspects of precursor and innovative character [14, pp. 12–15]. This would lead to the acknowledgement of projects that established new trends in the development of architecture at the time of their construction. These matters will be discussed in subsequent phases of the project. At the same time, from the perspective of the Polish research team taking part in the InnovaConcrete project consortium, it would be appropriate to consider both the significance of Polish concrete architecture on the scale of Europe, as well as the conservation problems associated with it.

5. Polish concrete heritage against the European background

In the discussion on the significance of Polish concrete architecture in the broad group of buildings that comprise European heritage, this paper limits itself to selected post-war projects. In comparison to the architecture built prior to 1939, it constitutes a field that has been identified to a much lesser degree. Furthermore, such objects are often perceived as 'undeserving' of the rank of heritage buildings, which considerably impacts the state of preservation of the architecture from the period of the PRL. This is demonstrated by, among other factors, the relatively small amount of post-war buildings that have been placed under conservation in the entire country [17, pp. 87–88]. The changes that are taking place[1] in this field appear to be progressing too slowly in relation to ongoing building decay. At the same time, the massive amount of material concerning 'the lowborn'[2] has forced discussion of only a few distinct examples.

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[1] One example of positive changes is, among other things, placing the SKM station and the 'Warsaw Central' train station on the Masovian Voivodeship historical monuments registry list. The entry procedure was initiated in 2018 (at the time when the InnovaConcrete project was starting, the works of A. Romanowicz and P. Szymaniak were not yet under conservation).

[2] A term used to describe the architectural heritage of the PRL, popularised by Filip Springer (F. Springer, *Źle urodzone*, Warszawa 2011), its first recorded use being by Jakub Lewicki (J. Lewicki, *Jak ocalić co cenne z architektury XX wieku*, „Gazeta Wrocławska" 18.12.2008).

Fig. 3. 'Okrąglak' – former department store in Poznań [by author]

During the course of the initial selection, a number of buildings that represent interesting and innovative design solutions but had not gained acknowledgement in the eyes of the consortium for various reasons were rejected. These included two buildings built in Łódź in the 1950s and 1960s: a sports hall (the Palace of Sport) and the Łódź University Library (the BUŁ). The first building was designed by Włodzimierz Prochaska. Its innovative structural system was based on eight concrete parabolic arches with a span of 72.5 m and a height of 28.5 m [22, p. 419]. A movable formwork was used to cast them, marking its first ever use in Poland [5]. Prefabricated reinforced concrete shells were placed on the arches. The structural elements of the hall were built in 1948. The conceptual design of the BUŁ building was developed during the same period. The authors of the design, Edmund R. Orlik and Eugeniusz Budlewski, used a then-pioneering prefabrication system, with concrete elements being manufactured on-site [5, p. 189]. The elements that comprised the structure included H-frames, reinforced concrete beams, prefabricated wall elements and floor slabs (which were replaced with ribbed slabs in the main building) [11, p. 332]. The facades were given a rectangular-patterned reinforced concrete finish with lesenes and parapets, while the main entrance was accentuated with a reinforced concrete cantilever roof. The rejection of the candidacy of Łódź>s Palace of Sport appears understandable in light of the fact that qualities that are key from the point of view of the IC project are either almost unobservable or are a result of the construction process itself. Furthermore, buildings of a similar function (sports and entertainment halls) were strongly represented on the '100 list'. It is difficult to accept the rejection of the BUŁ building, which would not only constitute another example of the

rather small group of buildings with a prefabricated structural system, but is also an example of the use of different structural systems within a single building (column and slab structure, cantilever structure, prefabricated facade elements).

Among the buildings that were too easily rejected during the initial selection stages, of note is the 'Okrąglak' Poznań Department Store by Marek Leykam. Fortunately, the initial decision was changed and the building has been finally included on the '100 list'. This constitutes an exceptional example of the use of an innovative prefabrication technology to create an original, modern form of a retail building. The building is well-entrenched in the public consciousness and the value of the 'Okrąglak' is undisputable (as confirmed by its placement on the historical monuments registry list in 2003). However, the matter with the 'Bunkier Sztuki' Gallery of Modern Art building in Krakow presents itself differently. Designed by K. Tołłoczko-Różyska, the building constitutes an example of an interesting combination of late modern architecture with the historical context of its surroundings (including a seventeenth-century granary). The building, which features a concrete skeleton structural system, has a particularly significant value in the form of its external walls, with a distinct texture of a three-dimensional formwork (the work of S. Borzęcki and A. Hajecki), as well as the sculptural, monolithic concrete roofs over its entrances [23, pp. 117–120]. The Bunkier, although it had been placed on the initial list, did not garner enough acknowledgement to make it to the final 100.

6. Lost values

The fact that from among over 200 propositions, only five were multi-family residential buildings built using the panel block system appears quite telling[3]. Both in post-war Western Europe and on the other side of the Iron Curtain, prefabricated housing blocks permanently altered the landscape of cities and towns, in addition to leading to a social revolution of sorts. Plans of placing the residential towers at Plac Grunwaldzki in Wrocław, designed by Jadwiga Grabowska-Hawrylak, on the '100 list' were abandoned because of their thermal modernisation. However, while there can be no doubt that the functionality of residential developments should constitute a priority, it should be admitted that, along with the addition of the external layer of thermal insulation, the authenticity of the buildings has been lost. In initial proposals, alternative methods of increasing thermal insulation values had been discussed; however, traditional solutions were ultimately selected[4]. Thus, the buildings, which combined a skeleton structural system (H-frames) and three-dimensional prefabricated facade elements with varied surface textures [8, p. 377], have lost a part of their original

[3] The following were included: Ernst Thalmann's housing estate in Berlin, the Barbican Centre and the Brunswick Centre in London, Bijmelmeer in Amsterdam and Roskilde Amtsgaard in Roskilde.

[4] At the time of the writing of this article (November–December 2018), the administrators of the Polish Mother's Memorial Hospital in Łódź were facing a similar dilemma. The building, completed in 1984, has facades covered with distinct, bright reinforced concrete prefabricated elements. Architects have proposed installing thermal insulation on the inside of the building so as to avoid an irreversible alteration of the form of the building.

Fig. 4. 'Bunkier Sztuki' Gallery of Modern Art building in Krakow [by author]

value. Similar modernisation processes have become the fate of the majority of housing block estates built using panel block technology.

Whilst the thermal modernisation of multi-family buildings appears to be a fully justified activity, those cases of post-war heritage whose destruction has been either deliberate or unintentional are a cause for alarm. The neglected reinforced concrete roof at the Warszawa Śródmieście WKD train station was aimed to be placed on the historical monuments registry list in 2018. However, before this was performed, its twin structure, which A. Romanowicz and P. Szymaniak had designed in the western part of the station, was demolished in the 1990s. Wacław Zalewski, who was responsible for the conceptual design of the structural schemes of the Cross-City Line pavilions in Warsaw, also created a series of interesting reinforced concrete roof structures for industrial buildings. Some of these were demolished, like the hall of the Defenders of Westerplatte industrial plant in Łódź (architects: Alina and Aleksander

Dębski) [6, p. 32]. Others, due to neglect, have lost their past values, as demonstrated by the factories in Mińsk Mazowiecki or Wyszków [13, p. 207]. The 'Runotex' factory in Kalisz, which has been included in the InnovaConcrete project – and whose owners have not only refrained from separating its ties with the PRL-period history of the plant instead even reminding others of it [25] – has survived in a relatively good condition. The owners' stance appears particularly valuable to the history of Polish twentieth-century architecture in light of the words of Zalewski himself, who stated that the greatest challenge in his career had been "thin wall structural systems – the hall in Łódź […], the factories in Mińsk Mazowiecki, Wyszków..." [20, p. 32].

The decay of factory buildings in Wyszków or Mińsk leads us to the Silesian Scientific Institute that has been mentioned in an earlier part of this article. The impressive, brutalist massing of the building, designed by S. Kwaśniewicz (structural system design: Franciszek Klimek) was the result of site-specific conditions, which sort of forced the design to include full external walls and have interior spaces that face an internal courtyard [15, p. 111]. At present, the building is in a state of ruin, and its legal state (the property belongs to several owners) is not conducive to formulating optimistic scenarios concerning its future. Is the placement of the institute on the closed list of selected European buildings justified? The consortium underlined its formal values and innovative functional solutions, which, however, lose their significance in light of the considerable decay of its structural substance.

7. Conclusions and future plans

Activities planned for the years 2019–2020 as a part of the InnovaConcrete project will cover the finalisation of on-site studies and the extension of activities that raise public awareness of the role of twentieth-century concrete architecture in the creation of European heritage. Apart from the well-described '100 list', a narrowed-down list of twenty-eight buildings is planned, on which every EU member state will be represented by a single selected building/structure. Previous work on the project has made it evident that the selection will require using both a more fine-tuned methodology, as well as, in all likelihood, arbitrary decisions.

From the perspective of the Polish research team, the conclusions drawn from the discussion presented above and concerning the previous work as a part of the InnovaConcrete project can appear pessimistic. Many buildings that stand out in terms of design and technical innovation have been permanently destroyed or altered. The most outstanding example of the 'concrete heritage' of the architecture of the PRL period – the train station in Katowice, built in 1973 (Wacław Kłyszewski, Jerzy Mokrzyński, Eugeniusz Wierzbicki) was demolished in 2010 despite protests by Polish and international circles[5]. Fortunately, as the years have passed, so has the situation of the heritage of post-war modernism in Poland been significantly

[5] Architectural and heritage conservation communities were among those who were protesting, with letters sent to authorities by ICOMOS and Europa Nostra.

improving. This is demonstrated by more and more buildings being placed under conservation, e.g. Poznań's 'Okrąglak' or the 'Warsaw Central' railway station (initiation of proceedings in 2018). Joint efforts as a part of projects of European significance constitute a chance to expand our research perspective. Sharing experience on the international stage makes it possible not only to make use of the achievements and knowledge of research and scientific centres from other countries, but also to restore works of Polish post-war architecture to the mainstream discussion of the heritage of the twentieth century in Europe.

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From *Architecture Without Architects* to architecture after architects

Od *Architektury bez architektów* do architektury po architektach

Abstract

The ideas presented by Bernard Rudofsky in the exhibition and book entitled *Architecture Without Architects* are being proposed by the author as the starting point of discussion on the condition of the architectural profession. Rudofsky focused the world's attention on architecture formed by the forces of Nature and as a result of natural development processes. The article raises the question of the future of the architectural profession seen from the perspective of the present time, whilst the technological development, in particular automation and computerization of design and construction processes, has gone so far that it is possible in the near future that man might be replaced by machines, which in turn may lead to a deep change in the architectural profession, or to its eventual complete disappearance

Keywords: architecture, artificial intelligence, AI, nature and architecture, BIM

Streszczenie

Autor za punkt wyjścia do dyskusji przyjmuje idee przedstawione przez Bernarda Rudofsky'ego w wystawie i książce zatytułowanej *Architecture Without Architects*, idee architektury formowanej siłami Natury i w wyniku naturalnych procesów rozwojowych. Następnie stawia pytanie o przyszłość architektury widzianej z perspektywy czasu obecnego, w którym rozwój technologiczny, w szczególności automatyzacja i komputeryzacja procesów projektowania i budowy, zaszedł tak daleko, iż możliwe jest w nieodległej przyszłości zastąpienie człowieka przez maszyny, co w konsekwencji doprowadzić może do zmiany charakteru zawodu architekta lub do jego częściowego zaniku.

Słowa kluczowe: architektura, sztuczna inteligencja, AI, natura i architektura, BIM

1. Architecture without architects

In the year1964 Bernard Rudofsky[1] opened his famous exhibition entitled *Architecture Without Architects* [1], accompanied by a book of the same title, at the Museum of Modern Art in New York. The author states that "the history of architecture written and taught at Western universities focuses on a few selected cultural circles" [1, p. 2], and that academic textbooks describe the development of architecture in its late stages, bypassing the early stages, emphasizing mainly the role of eminent architectural stars, or also rulers and patrons and their magnificent residences, tombs, sacred buildings, public buildings, pushing to the background a development history of construction serving the everyday needs of the majority of society, i.e. ordinary people. Rudofsky's goal was to overcome this stereotype and, through the exhibition, pay attention to architecture created anonymously, outside selected culture-forming centres, growing out of experience and local tradition of places, overlooked by such a selectively written history. Rudofsky also draws attention to the fact that man is not the only builder of structures designed to improve everyday functioning in the natural environment, whether it is protection against atmospheric conditions and danger or as constructions helpful in gaining food. Animals behave similarly, for example, chimpanzees are building sleeping platforms suspended on trees, or beavers are constructing dams on the river, etc. Nature itself creates fascinating forms and spaces convenient for human and animal use for shelter – caves, mounds, empty tree trunks, etc. The author of the exhibition wanted to emphasize his willingness to overcome the prejudices existing in developed societies to perceive the authenticity and mastery in the constructions of the so-called primitive, carried out in cultures and regions distant from civilization, not industrialized. To sophisticated forms emerging in a way resulting mainly from the tens of generations of experiences generated by anonymous members of local communities, in accordance with their own technical capabilities and with a specific understanding of the forces and laws of nature. Rudofsky also noticed that many so-called primitive solutions in vernacular architecture apply schemes and technologies to which the modern architecture of highly developed centres was only mature in the twentieth century. He cites "prefabrication, standardization, elastic constructions, natural ventilation, [...], light control" [1, p. 5] etc. As Rudofsky's exhibition and book has been very popular for over half a century, he teaches us to perceive and understand architecture created "without an architect" as a centuries-old building process in conditions of human proximity and dependence on the natural environment and depending on its laws, cyclicality and variability.

[1] Bernard Rudofsky, born on 13.04.1905 near Ostrava, he graduated from architecture at Technische Hochschule in Vienna (1928), from 1941 in New York, curator of many architectural exhibitions, author of publications on architecture, lecturer at MIT, Yale, Waseda University in Tokyo [7].

2. Architecture by architects and architecture of information

What is the current state and what might the near future of architecture look like? The conclusion that architects are currently designing buildings may seem trivial, but it may stop to surprise us if we realize that in the near future such a state of affairs may change, and the architect's profession may completely change. The architects of our generation are convinced that they control and create architecture (especially its forms) and control the direction of its future development. They are convinced that the quality of architecture is the result of knowledge, experience and talent, and perhaps also inspiration. Their ambition is to generate individual forms of expression and to send artistic messages of various forms of complexity and randomness, and to apply them into the spaces of our cities and landscape. The archetype of the architect – a modernist demiurge, capable of controlling and shaping architecture and modelling individual and social life on the scale of very complex systems, such as cities and societies, is constantly current and popular. We are still in the era of "architecture created by architects", of course bearing in mind all the external factors limiting architectural omnipotence – that is, the political, legal and economic factors in which the architect functions, and whose influence on the directions of development of our spaces remain dominant. However, we can already observe a strong drift towards a new perspective for architecture and the profession of architect: towards "information architecture". Since the introduction of the first computers to architectural practice in the 1980s, the field of architecture has increasingly been shaped by the imagination and knowhow of the

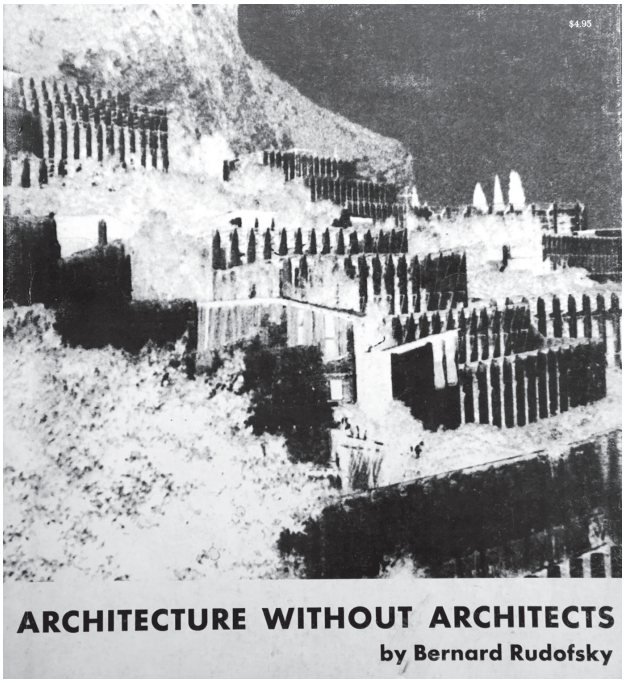

Fig. 1. Book cover – Bernard Rudofsky, Architecture Without Architects [by the author]

information world, software engineers, sociologists, data analysts focused on university and corporate research institutions dealing with urban studies and CAD design technology. Architects quickly understood that computers were becoming an indispensable tool for the proper analysis of the growing quantities of information related to the complex scale of their tasks. The last twenty years of architecture has been a clear and decisive success for digital technologies of urban structure analysis, and sociological research related to the space of architecture, cities, etc., which support the design process.

The influence of computer technology on the design of architectural forms in the period of last twenty years can be called spectacular. It was a definite explosion of the architecture of lines and planes, of computer-generated curves, delight in the possibilities of individualizing architectural forms while maintaining the comparable cost of its production, although this situation may have already passed its climax and is slowly moving towards another change. Mario Carpo [5] described this style of line architecture and curves as "blob style", also known as spline style or digital rationalization. "It became the hallmark of the first digital age of the nineties, [...] With the collapse of the 'digital economy' the wave of digital enthusiasm and technological optimism in the late 1990s suddenly lost its power, and many design professions began to treat digital blobs as the most striking symbol of excess and technological delusions" [5, position 229].

Carpo notes that new trends in the design world will be associated with the so-called era of Web 2.0, which he describes as a "participatory network" – "When the dust settled, the new spirit and some new technologies led to the so-called Web 2.0, which means a participatory network, based on collaboration, interactivity, crowdsourcing and the end user – for which individual content will be generated" [5, position 238]. However, he adds that the transition to the mass network collaboration phase has not yet occurred – with one exception – "Except avant-garde experiments and, more importantly, except the technology family known as Building Information Modeling, or BIM – unanimously adopted by the construction industry, though reluctantly accepted by academic and design-related professions that strongly rejected the direction of technological and cultural development that would weaken (or in fact transform) some of their traditional copyright privileges" [5, position 238].

These opinions indicate that we are now witnessing the clash of two tendencies: one aiming at further technologicalisation of the design process supported by artificial intelligence, and the second "participatory" trend, arising in opposition, expressing anxiety about the loss of subjectivity in the author's creative process. The future of architecture will depend on which of these trends dominates the market.

3. Architecture after architects

It becomes justifiable to ask about the future of our profession at the moment when the first in the above tendencies will be able to dominate the architectural design market as well as the investment process, and will affect the methods of selling the final product,

i.e. buildings, flats, etc. Further technological development, in particular the automation of design and construction processes, may go so far that it will be possible in the near future to replace man by machines, both at the design and construction stage, and interestingly – also when it comes to the use of buildings! It should be mentioned that in terms of building function, a new type of facility has already been identified. The architecture of technology has emerged in addition to residential, public, industrial and other known types of architecture. New architectural objects appeared in our landscape in which the main user is not directly man, but machines. It is the architecture of powerful automated warehouses, server rooms, logistic centres, packing rooms, and other industrial facilities in which the production process is robotic and digitally controlled. This topic is the leading subject of the issue 01/2019 of Architectural Design, edited by Liam Young [6]. In the introductory article, he writes about the phenomenon of the emergence of gigantic data centres of such companies as Facebook, Google, Apple or Amazon built in Oregon: "These flickering buildings are more than just computational infrastructures, they are becoming the defining cultural constructions of our age. At a time when our collective history is digital, these blank forms are our generation's great library, our cathedral, our cultural legacy. Every era has had its own iconic architectural typology. The dream commission was once the church, Modernism had the factory and then the house; in the past decade we celebrated the decadent museum and the gallery. Now we have the data centre" [6, p. 10].

The construction of these objects is based on the new logic and measure, man is not a reference point in this case: "Ancient craftsmen once measured using parts of the human body: the cubit is based on the length of a forearm; the inch, the length of a thumb. Le Corbusier designed his buildings based around the Modulor, a scale he derived from the proportions of the human body. We once understood our world through systems that positioned ourselves, human scale, vision and patterns of occupation at the centre of the structures that we design. In the age of the network, however, the body is no longer

Fig. 2. Examples of buildings printed using 3D printing technology – carried out in Shanghai by Shanghai WinSun Decoration Design Engineering Co. [10]

the dominant measure of space; instead it is the machines that occupy the spaces that now define the parameters of the architecture that contains them – an architecture whose form and materiality is configured to anticipate the logics of machine perception and comfort rather than our own" [6, p. 11].

This type of building is still designed by an architect, but the jump towards the automation of the design process is small in this case. It involves formalizing the technological process and adapting to it the appropriate form and construction technology, laws of physics, etc. Architecture will always be the product of a special kind of skill related to the efficient use of these laws for utilitarian purposes to be achieved through the physical form of the building. In the near future, these skills will be implemented not necessarily by an architect or structural engineer, but by means of computers and appropriately programmed design algorithms combined with large databases.

Technological progresses, which take place in the production of building materials and methods of computer building design, both its construction and the entire set of installations necessary for the proper functioning of the building, allow for increasingly precise control of the functioning of the whole object as a real and functionally-oriented object. That is, adapting it to external natural conditions – geographical, topographical, climatic conditions, as well as controlling the assumed internal thermal, moisture, acoustic parameters of the object. As a result of this process, buildings become more and more energy-efficient and adapted to individual ergonomic and functional needs, and they are also cost-optimized in terms of implementation and operation.

Fig. 3. Example of a building printed using 3D printing technology – by Shanghai WinSun Decoration Design Engineering Co., Shanghai, China [10]

Fig. 4. A printed building completed in 2018 in Denmark by the COBOD company [11]

All types of design issues are now controlled and coordinated in constantly improving BIM (Building Information Modeling) which is becoming one of the key aspects of the construction and architectural design process. BIM software allows you to accurately coordinate the form of the building with installation projects, with the construction, with the selection of the appropriate architectural elements, such as walls, stairs, windows, doors, etc., and in effect gives you complete control of the whole, as well as individual subsystems of the building. The future BIM building remains a fully-controlled system during all phases of design, construction and operation. To paraphrase Le Corbusier, it becomes a new kind of "machine for living in" in this process.

It is easy to imagine the automated production of such "machines" using contemporary BIM design machines supported by the achievements of artificial intelligence (AI). The first step to creating an automated production process is to create databases containing legal regulations in the field of local urban planning and construction law, then regarding social, health and neighbourhood conditions (the task of psychology and sociology of architecture), further – the system of local administration and the procedure for obtaining approval of the documentation project. The next step is the databases of individual fields of construction technology, from calculation methods to construction and finishing details related to all construction sectors, as well as databases defining ergonomic minima of individual functions. Such work is being carried out in many scientific institutes, e.g. in the French CSTB (French Scientific and Technical Centre for Building) [3].

Fig. 5–6. The next phases of building printing – by Cobod [11]

Of course, all data containing examples of historical architecture should also be found in databases in order to be able to use and develop the best proven solutions in each type of building and to relate it to specific local cultural and climatic needs, etc. The next step is to create expert systems that help to organize information hierarchically. This information in turn will feed the next stage of the system, which is the simulation of the design process. Its creation must be based on a thorough analysis of the process of making subtle design decisions that assume the possibility of considering new data during the design process, as well as the possibility of changing it (fragmentation, decomposition and self-modification), that is, considering the opportunity to learn [2, p. 167].

Probably in the near future self-learning architectural software of the new generation AI-BIM (Artificial Intelligence – Building Information Modeling), will be able to develop to the point that it will be able to replace architects, structural engineers, and HVAC engineers in design work. What's more, every entrepreneur, equipped with the appropriate AIBIM software, will be able to "do it yourself" design and construction. He will simply enter the coordinates of the property boundaries, and further – the parameters of the desired building – that is, the appropriate number of apartments, rooms, number of floors, expected construction cost per square metre, and the machine will analyze this data and suggest a solution to the task, taking into account the laws of physics, building regulations, formal guidelines from the local master plan, local climate, and the spatial conditions of the neighbourhood, as well as financial feasibility, etc. More advanced versions of the program will be able to offer additional variants with individualized features of the building form, generated on the basis of algorithms taken from analyzes of historical objects. Eventually, if the developer's ambitions are aimed at further individualization of the architectural form, the generating process of forms can be based on other types of algorithms, e.g. researching the demand for specific forms in a given location among local community, based on conclusions resulting, for example, from big data analysis[2]. If, however, the formal result aims to surprise all connoisseurs of architecture with a certain manneristic unpredictability and uniqueness, the generation of architectural forms could be generated, for example, based on algorithms drawn from the theory of catastrophes[3].

In the next stage, i.e. after preparation the construction documentation, the AI-BIM software will send the project data to the appropriate computer in the Department of Architecture of the City Office, where the computer will instantly check compliance with local law, and then automatically send a building permit, the finality of which will be confirmed in time real-life computers by all parties and will not be subject to endless further discussions, interpretations, cancellations, etc. The client will continue to press the next

[2] "Big Data" is a trend to look for, collect and process available data. It is a method of legally collecting information from various sources, and then analyzing and using it for your own purposes. As a result, a consumer profile is created, which is later used, for example, to increase sales. The most important is the practical use of the conclusions flowing from them, and not the mere collection of data [8].

[3] Catastrophe theory – mat. theory describing abrupt changes in the state of various systems. Particular attention is paid to models showing resistance to small disturbances (structural stability). The author of the disaster theory is Rene Thom (*Stabilité structurelle et morphogenèse*, 1972), and the prominent propagator of it – E.C. Zeeman. The theory is used in physics and technology, as well as in sociology, economics, linguistics and others [9].

Fig. 7. 3D house in Chattanooga, Tennessee, USA, 2017, architect: WATG's Urban Architecture Studio and Branch Technology [12]

button on the keyboard, which will send the project to construction companies offering 3D printing construction. The building will be printed in a short time, basically without the need for human supervision.

The 3D printing technology for residential buildings is already up-to-date and applied in practice. The first such residential buildings in the USA, in China and in Europe have already been constructed. Refining this technology and fully automating the design process is a matter of a short time, maybe one generation, and probably our current students will in a decade or so treat these current novelties as everyday practice.

Marketing and sale of offices spaces or apartments will be individualized – the offers will be immediately sent to selected potential buyers. These will probably be precisely targeted sales offers, suitably selected in terms of personality traits for users of Google, Facebook, Instagram and other social media, or similar tools generating information about users, referred to as "Big Data". Proper analysis and ordering of these data in terms of adequately selected psychological personality theory (e.g. OCEAN[4] type or other, more extensive and precise) [4] will allow screening of recipients and reaching a targeted sales offer to those whose psychological profile guarantees acceptance of a given project. As a result, a quick purchase will be not a surprise.

It is quite probable that the future of architecture will be such a pragmatic, albeit highly sophisticated and individualized architecture of intelligent machines – devoid of the traditionally understood artistic vision, intentions, individuality of the creator and emotions deliberately caused by artistic play with form and material – architecture that is a post humanist

[4] O.C.E.A.N. – one of the psychological personality theory, created by Paul Costa and Robert McCrae, developed among others by prof. Lewis Goldberg (University of Oregon). Theory assumes that human personality can be described through a combination of five features of The Big Five, these are: Openness (openness to experience), Conscientiousness (conscientiousness), Conscientiousness (extraversion), Agreeableness (agreeableness) and Neuroticism (neuroticism).

incarnation of the contemporary Zeitgeist. This architecture will be able to adapt perfectly to the natural environment, will implement the principles of sustainability in all possible aspects and, very importantly, will be perfectly adapted to the needs of each end user, because it can be perfectly anchored in its individual personality profile. It will probably guarantee the full satisfaction of the user as well as local communities.

It is difficult to predict whether the above perspective of the development of architecture--related technology and the architectural profession will gain an advantage over tendencies which contest this direction, but AI technology is progressing and its further development seems inevitable.

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Collaborative Planning for Sustainable Urban Infrastructure in Frankfurt am Main

Planowanie współpracy zrównoważonej infrastruktury miejskiej we Frankfurcie nad Menem

Abstract

Infrastructure planning in most cities is a process of sectoral implementation which produces independent sectoral solutions to urbanisation issues. With the advent of sustainable practices, along with the challenges posed by climate change, cities are discovering important synergies among urban infrastructure sectors which are being used to reduce the urban footprint. In the need for sustainable infrastructure, the city of Frankfurt am Main, although operating in a sectoral manner, has learned from past experiences and has progressively developed a collaborative approach to infrastructure planning. This collaborative approach increases the possibilities for trans-sectoral projects and reduces the consumption of natural resources. This paper showcases interesting sectoral and trans-sectoral projects in the infrastructure sectors of energy, water, wastewater, solid waste and urban agriculture. The showcased projects have been selected from a study of 36 operational, programmatic and educational initiatives implemented by the city.

Keywords: collaborative planning, sustainable infrastructure, trans-sectoral projects, renewable energies

Streszczenie

Planowanie infrastruktury w miastach jest procesem wdrażania sektorowego, który przynosi rozwiązania problemów urbanizacyjnych. Wraz z pojawieniem się zrównoważonych praktyk obok wyzwań związanych ze zmianami klimatu miasta zaczęły odkrywać ważną synergię między sektorami infrastruktury miejskiej. Korzystając z wielu lat doświadczeń, architekci i urbaniści z Frankfurtu nad Menem stopniowo rozwijają swoją współpracę w planowaniu infrastruktury. Podejście oparte na współdziałaniu zwiększa możliwości projektów międzysektorowych i zmniejsza zużycie zasobów naturalnych. Niniejszy artykuł przedstawia interesujące koncepcje sektorowe i międzysektorowe w zakresie infrastruktury sektorów energii, wody, ścieków, odpadów stałych i rolnictwa miejskiego. Prezentowane propozycje zostały wybrane z 36 inicjatyw operacyjnych, programowych i edukacyjnych realizowanych przez miasto.

Słowa kluczowe: wspólne planowanie, zrównoważona infrastruktura, projekty międzysektorowe, odnawialne źródła energii

1. Introduction

Frankfurt am Main, 740,000 inhabitants in 2018, is a dynamic metropolis at the heart of the FrankfurtRheinMain Region in western Germany. The employment opportunities fuelled by financial services have not only created unexpected population growth in the city and the region, but also a series of challenges in terms of urban infrastructure provision and affordable housing to respond effectively to the needs of existing and new residents as well as commuters. The municipal departments in charge of infrastructure and urban planning have responded to these urbanisation challenges by implementing incremental collaborative planning processes, focusing the development of the city on sustainability, environmental protection and mitigation measures to cope with climate change.

This article is the summary of an ongoing empirical investigation into the planning process for sustainable urban infrastructure in Frankfurt and a recollection of the projects implemented by the city. The research examines five sectors of urban infrastructure provision, namely energy production and provision, water provision, wastewater management, solid waste management, and urban agriculture. This research about infrastructure planning and implementation in the city highlights the importance of project-driven collaborative planning processes, along with the involvement of a diversity of urban actors in the planning and implementation process. Likewise, the research identified some trans-sectoral infrastructure projects which increase the effectiveness of investment in urban infrastructure for the city. This paper will describe the most prominent projects, categorising them into practice-oriented, programmatic and educational. In the same way, for each category an abridged stakeholder analysis has been created to identify the typology of actors involved in the provision of urban infrastructure in Frankfurt.

The research sub-project *Urban Planning and Capacity Development* at the Frankfurt University of Applied Sciences is part of a larger research project: *Rapid Planning – Sustainable Infrastructure, Environmental and Resource Management for Highly Dynamic Metropolises*, funded 2014–2019 by the German Federal Ministry for Education and Research (BMBF). Frankfurt was selected as a reference city because of its size, population growth rate, and the city's position in the German and European economy. The project recognises Frankfurt as a good example of sustainable planning practices which have resulted in a good quality of life, providing urban infrastructure with a focus on environmental protection [9]. The research on Frankfurt as a reference city has two main objectives: to identify the urban infrastructure projects that promote sustainable development in the city, and to describe and analyse the planning system in Frankfurt with the instruments and processes utilised by the City Planning Department in the search for a balanced urban environment and a better quality of life in the city. This paper addresses the sustainable infrastructure projects; the analysis about the planning system can be found in the article *A flexible system for localised sustainable development* published in 2018 in the journal Technical Transactions [10].

2. Ambitious Sustainable Development Goals

Frankfurt has defined ambitious goals for urban development, following the guidelines of the German Federal Government and the European Union. The city applied for the *European Green Capital Award* in 2014 and, since then, has implemented a series of initiatives to increase and preserve the quality of life in the urban core. The submission of Frankfurt for the Green Capital Award was mainly based on three service provision sectors: energy performance, sensible water usage and e-mobility [6]. Although Copenhagen won the award in 2014, the nomination as a finalist served as the basis to promote more sustainable development projects and create a sustainable vision for Frankfurt. The city extended the scope of the green city vision to include other urban sectors, defining four core areas to promote sustainable urbanisation: *Economy and consumption, Sustainable mobility culture, Planning and construction in dense urban areas, and Climate and open spaces* [19].

Sustainable development has been a goal in all German cities for more than a decade, leading municipal governments to adopt formal environmental protection policies along with measures for the provision of sustainable urban infrastructure. Hence, simultaneous to the process of applying for the Green Capital Award, the city developed a sustainable energy concept following the national and international guidelines for urban sustainability. In the form of *Master Plan 100% Climate Protection,* this concept set specific sectoral goals for reducing the consumption of natural resources and decreasing the urban footprint of the city regarding energy production [12]. The research has shown that the implementation of sustainable infrastructure provision policies for reducing the impact on the built environment has resulted in the generation of trans-sectoral synergies among different infrastructure sectors while increasing the efficiency of investments in urban infrastructure for the city. The analysis of infrastructure provision programmes and projects in Frankfurt suggests that the concept of trans-sectoral synergies in the city has been increasingly permeating the infrastructure planning process for years; thus, a project--driven collaboration scheme has been developed which depends on formal communication channels among the relevant municipal departments for each project and agreement among public officials on a common sustainable vision for the future. Initiatives such as *Master Plan 100% Climate Protection* and *Frankfurt Green City* look at urban development in a holistic way, involving not only different sectors of urban infrastructure in the process but also different urban actors.

Figure 1 shows the involvement of the public actors in the different infrastructure sectors revised by the Rapid Planning research project in Frankfurt. The direct or indirect participation of diverse stakeholders in one specific sector illustrates the synergies between the sectors of urban infrastructure in Frankfurt; for each sector the key actor is a municipal department that controls the planning process and promotes trans-sectoral initiatives, as well as the involvement of other relevant municipal departments. As an example, energy provision projects are defined and controlled by the Municipal Energy Agency, which looks at implementing clean energy-provision technologies and reducing energy consumption. With these objectives in mind, the energy projects also involve the waste and wastewater

sectors by utilising waste products for the production of clean energy, i.e. cogeneration plants that produce energy and heat from biomass, household bio and solid waste, and sludge from wastewater treatment. These energy projects demand collaboration between public actors such as the Municipal Energy Agency, the City Planning Department, and the Environment Department. They also require cooperation with semi-public and private actors such as the waste management company (FES) and local community organisations, e.g. in the case of using the residues from the cogeneration process for compost.

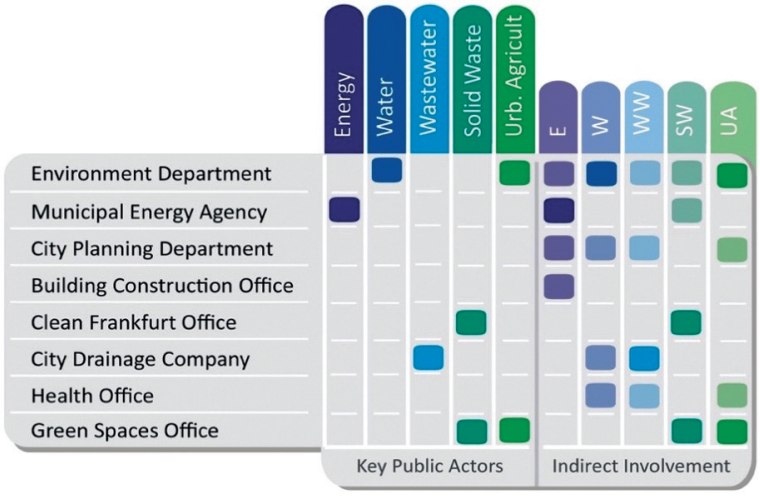

Fig. 1. Involvement of municipal departments and public stakeholders in the infrastructure sectors (source: Global Urbanisation Research Team FRA-UAS)

3. The Impact of the Energy Sector in Urban Planning

The establishment of ambitious environmental goals is based on the objective of providing the city with 100% renewable energy by 2050 [3, 13]. The methods used to achieve this objective are the transition from fossil fuels to renewable energy sources, along with raising awareness among the population and promoting the reduction of energy consumption in households and industry. Utilising new technologies for renewable energy reduces CO_2 emissions and is also closely linked to the depletion of natural resources in other sectors, e.g. energy, water, and a reduction in waste products going to landfills.

Renewable energies are changing not only the process and attitudes of planning for buildings and urban infrastructure, but also the perception of the city. These policies are collected in *Master Plan 100% Climate Protection*, which establishes the goals for the city. The Master Plan defines different scenarios for the provision of clean energies, as well as goals for reduction of CO_2 and consumption of fossil fuels in the city. It develops general guidelines for the public and the private sector in terms of energy planning until the year 2050 (Fig. 2).

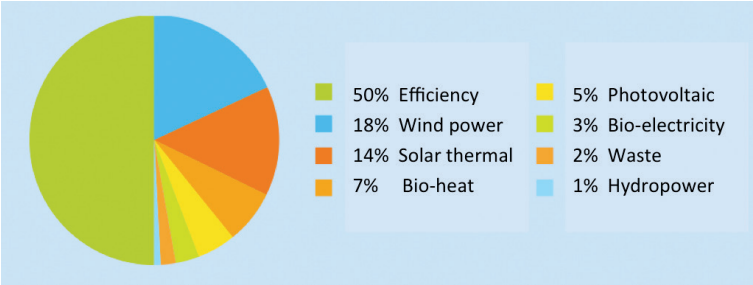

Fig. 2. Scenario of energy provision in Frankfurt am Main in 2050 [2]

3.1. Clean Energy Provision Strategies

The sustainability mandate of the city has led to the implementation of a diverse set of measures for the production of clean energy; examples include district cogeneration plants, encouraging the use of photovoltaics, bringing together diverse urban infrastructure sectors to reduce the city's input of resources and output of waste, and reusing biomass and solid waste products for the production of heat and energy. As a result of the climate change policies implemented in the country and the city in recent years, the use of clean energy has grown in the city and met 50% of the electricity demand in 2014 [15]. Technologies such as photovoltaics, thermal and wind power, and cogeneration from waste and biomass have become commonly used by public and private buildings, and these new technologies are now a possible source of income for households and businesses, e.g. photovoltaic panels on roofs and facades as private investment.

3.1.1. Solar Roof Frankfurt (Solardach Frankfurt)

A promotion programme for photovoltaic roof panels has been developed with the support of the semi-public energy company Mainova and the public housing company ABG Frankfurt Holding. Several systems have been developed and the company offers tenants an opportunity to purchase a share in photovoltaic plants. Photovoltaic systems help not only to produce environmentally friendly electricity and to involve citizens, but also to earn money for the citizens and for the city [3].

3.1.2. Cogeneration

Combined heat and power (CHP) generation systems are an efficient way of producing electricity and heat simultaneously using biomass or waste products. In CHP the residual heat that is generated in the production of electricity is used for heating purposes. The main advantage of cogeneration is that the system uses 90% of the engaged energy and saves up to 40% of primary energy, whereas in conventional power stations 60 to 70% of the primary energy is lost in production [3]. This process reduces carbon emissions and the carbon footprint of the city, and these power plants are lucrative and eco-friendly [27].

In Frankfurt cogeneration is an essential part of energy planning. The city is committed to the European *CHP goes Green* programme, which promotes the increased use of renewable energy sources from cogeneration. Frankfurt operates more than 200 decentralised facilities and has three major cogeneration-based district heating networks. In total they efficiently produce about 50% of the power and supply large parts of the city with heating, such as Frankfurt Airport and office buildings [3].

The design of cogeneration power plants in Frankfurt is linked to urban planning. The Municipal Energy Agency annually collects information about cogeneration processes and results. The analysis of these data, its impact and possible improvements are discussed with the operators of the power plants in order to improve the cogeneration process. The discussion and sharing of experiences between the involved stakeholders are very important for achieving the sustainable goals of the city.

3.2. Energy Planning beyond Provision

Programmes such as *Solar Roof Frankfurt, Energy Renovation, Ecoprofit* and *Frankfurt Saves Energy* are collaboration projects between the Municipal Energy Agency, the City Planning Department, the local economy, private households and organisations – all supported by effective public relations and run by external experts. These programmes aim to reduce energy consumption and provision costs while protecting natural resources.

3.2.1. Energy Renovation

The Municipal Energy Agency also functions as consultant for private homeowners who want to increase the energy efficiency of their homes. It provides guidelines for the energy--saving renovation of private buildings, information on legal requirements and planning and implementation measures for special features of historical buildings, information on better insulation techniques and guidelines for passive house components. Moreover, the city has various support programmes, among others from the City Planning Department and the KfW banking institute, that can help to finance renovations and modernisation measures related to energy retrofitting [3, 27].

3.2.2. Ecoprofit – Ökoprofit

Ökoprofit is a pillar of *Master Plan 100% Climate Protection* in the corporate sector and is directed at city companies and operational facilities which want to improve their ecological performance and profit from improved climate-friendly technologies and practices. The programme gives companies access to environmental and energy management systems which save costs, use natural sources, and reduce negative effects on the environment. Ökoprofit focuses on individual counselling, joint workshops and networking among participating companies [4].

3.2.3. Frankfurt Saves Electricity (Frankfurt Spart Strom)

Frankfurt Saves Electricity is a support programme offered by the Municipal Energy Agency, which combines environmental and economic benefits for its participants, e.g. Frankfurt's private households, companies, associations, and community centres, and the city as a whole. The programme helps small and medium-sized enterprises to analyse their energy consumption and implement energy-saving measures. The programme also offers a financial incentive in the form of a cash bonus reward depending on the amount of the households' electricity savings [5].

3.2.4. Passive Houses

Passive houses (Fig. 3) are energy efficient, requiring around 90% less energy than regular buildings. As one of the strategies to achieve the goals of *Master Plan 100% Climate Protection*, all city-owned buildings and other municipal projects must be constructed following passive house standards, and energy-efficient components must be used for new constructions or refurbishment work [16]. The city leads by example in the reduction of energy consumption by implementing urban development policies in which all public buildings adopt the passive house standard by utilising solar, wind, thermal, and insulation technologies. The city also promotes and encourages the use of renewable energy sources for private developers by providing advisory services. The decision of the municipality to take public buildings up to passive house standards has made Frankfurt a hub for passive houses in Europe.

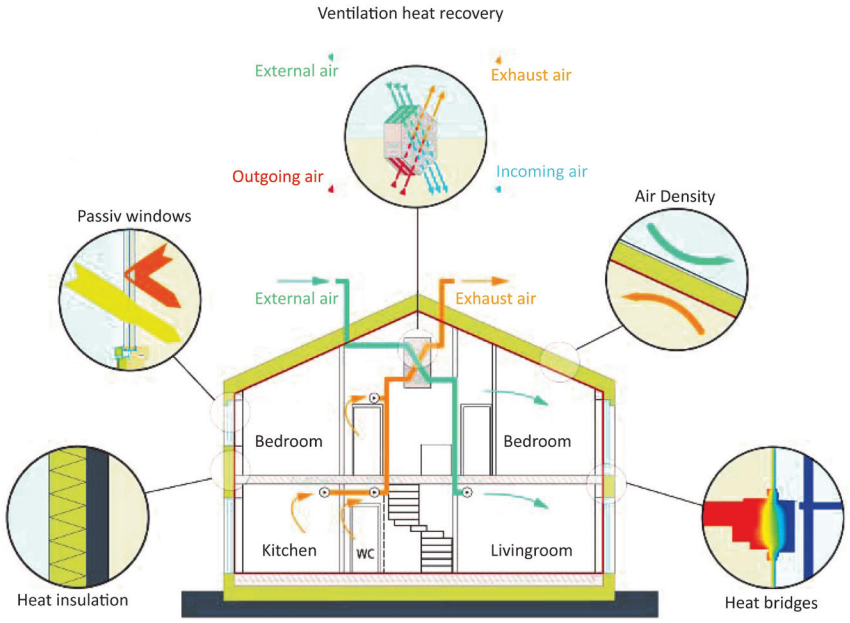

Fig. 3. The five basic principles of passive houses
(source: Passivhausinstitut, image modified by the Global Urbanisation Research Team FRA-UAS)

4. Environmental Protection and Climate Change Mitigation

The impact, participation and involvement of the city of Frankfurt on the region is regulated by the *Regional Authority (Regionalverband FrankfurtRheinMain)*, which comprises 75 municipalities in the metropolitan and surrounding area [11]. This institution's function is to create space for discussion and conflict resolution between municipalities, bringing them to agree on regional development policy in order to secure a good quality of life in the region. Regulations to protect green areas around the urban perimeter facilitate monitoring and quality control of the natural resources. These regulations also have a direct impact on the planning processes of the municipalities in the region, supporting efforts towards the conservation and protection of the environment.

4.1. Synergies between the Water Sector and Green Infrastructure

The strict federal regulations that the city must follow in the quality control of water sources demand the strong involvement of municipal departments in the management of provision, delivery, and collection systems. Therefore, the main actors involved in the water sector are the City Planning Department for definition of land uses, the Environment Department for control and monitoring of water quality, and Mainova, a semi-public service-provision company in which the municipality is the major shareholder. Other public and private actors are involved in educational and programmatic projects focused on raising awareness about the need to reduce water consumption in households or promoting new technologies for increasing the efficiency of water use in the industrial sector. The implementation of programmatic and educational projects, along with the improvement of technologies in the water sector, have resulted in a decrease of water consumption from 223 l/day per person in 1980 to 158 l/day in 2014 [28].

Water provision is a health-sensitive issue in cities and must be managed with the highest quality standards and specific legal regulations. The protection of aquifers demands the absence of polluting activities in the surrounding green areas; therefore, the implementation of water sector projects which involve other infrastructure sectors is difficult due to federal regulations and the health hazards of mishandling water sources. However, there is a clear relationship between clean water and the urban agriculture sector: responsible, pollutant-free, organic agricultural production should be coupled with water provision planning to protect aquifers whilst efficiently utilising the soil around the protection areas.

4.2. Wastewater Management, a Public Responsibility

Wastewater treatment is controlled to the highest standards in the city, which also implements new technologies and initiates trans-sectoral projects in order to reduce the output of waste products. Similar to the situation in the drinking water sector, the wastewater sector is regulated by federal laws which ensure that treated wastewater is free of harmful pollutants and can be delivered back to water bodies where the treated water infiltrates the

soil. However, in the case of wastewater the stakeholders are 100% public and, except for special agreements with neighbouring municipalities, the wastewater sector is concerned only with the collection, transport and treatment of wastewater within the city borders.

Fig. 4. Rainwater collection and infiltration areas in Riedberg District, Frankfurt am Main (source: Global Urbanisation Research Team FRA-UAS)

The challenges of the wastewater sector are related to the flow rate capacity of the sewage system to cope with an ever-increasing flow from urbanisation growth. The sewage system in Frankfurt needs expansion and renovation; in the new developments, the city has implemented a separate collection system for rainwater in flood-prone green areas, facilitating the direct infiltration of rainwater into the soil [23]. Rainwater infiltration also reduces the flow of sewage water going into the system, thus reducing the need for expansion of the sewage system. Reusing rainwater and greywater for gardening or industrial purposes has also been promoted in the city in order to reduce the demand for potable water [21]. In the same way, the rainwater collection areas are also green public spaces which on dry days can be used for recreation and leisure for the community.

The inclusion of rainwater collection and infiltration areas directly in the urban design of new neighbourhoods in Frankfurt, such as the new north-western district of Riedberg [23], highlights the collaborative approach between the City Planning Department and the Municipal Environment Department. Both departments work together to introduce elements of environmental protection and climate change mitigation in planning procedures.

Designing usable green spaces that are also functional for rainwater infiltration in urban areas decreases the pressure on the wastewater collection system, while allowing the replenishment of aquifers in the surroundings.

4.2.1. Sludge Dewatering and Incineration Project

Additionally, as an approach to trans-sectoral planning and resource efficiency, the collaboration between the City Planning Department, the Environment Department, the City Drainage Company and the energy provision company Mainova has produced a trans-sectoral sludge dewatering and cogeneration project that combines the energy and wastewater sectors by producing electricity and heat from burning the sludge left by the wastewater treatment process, and thereby also reducing the waste going to landfills. Sludge incineration is one of the most environmentally friendly and economically effective methods of disposing of sewage sludge [14, 26].

4.3. Reducing, Reusing, Recycling for Waste Collection

The waste management process in Frankfurt focuses on four recycling processes: *reuse, recycle, transform* and *compost*. *Reuse* is based on the repair of large electronic appliances and furniture; these are collected and fixed or repurposed for further use. Waste products made out of plastic, paper and metal go through the *recycling* process, where they are sorted and sent to the processing station. *Transformation* or thermal recycling is coupled with CHP processes, turning residual waste products into heat and energy by means of incineration in cogeneration plants. Finally, the outputs of the thermal recycling and bio-waste are processed into *compost* to be utilised in agriculture and gardening.

In order to reduce the consumption of plastic bottles, a refund fee is included in the price of each plastic and glass bottle, which prevents plastic bottles from going into trash bins or littering public spaces. In the same way, many supermarkets have banned single-use plastic bags, promoting reusable bags for shopping.

4.3.1. Waste Collection at the Household Level

The main concept behind the charging system is financial incentives for environmentally friendly behaviour; properly separated waste and reduction allow residents to save money. In addition, the free collection of bulky waste on demand and the delivery of harmful substances to specific collection centres prevent illegal dumping and environmental damage. The Environment Department is officially responsible for controlling and monitoring waste management and street cleaning, while the semi-public waste management company, FES, provides the service and all the necessary equipment [18].

The waste collection services are provided by different companies associated with FES. The city finances the waste management operation with the fees charged to residents and businesses, which operate under two payment modalities: standard fees and variable fees. A resident or

business can choose between the fee modality, and these fees finance the collection services, the service vehicles, personnel, administration, as well as management of sorting, recycling and disposal services. The standard fee is a fixed amount paid by every household and commercial establishment in Frankfurt. With the standard fee, FES also provides waste disposal containers. The collection of bulky waste is included free of charge up to 13 times a year. The variable fee is charged according to the volume of the waste and the frequency of the collection service [18].

4.3.2. Waste Management, a Multi-Stakeholder Trans-Sectoral Opportunity

The waste management system is a good example of joint work between citizens and the private and the public sectors in Frankfurt. The collection and disposal of waste products rely heavily on educating citizens and involving them in the separation of waste products at source, e.g. bio-degradable or light packaging, paper, and residual waste, etc. Separation is the first step in the waste management process and is aimed at reusing or reducing the amount of residual waste going to landfills.

Besides the benefits for the environment, a good waste management system based on separation, and recycling attracts private investors. Waste management has become a niche for businesses making a profit from the recycling, reuse or repurposing of waste products. The involvement of the private sector provides an enterprise-like management style, increasing the efficiency and facilitating technological upgrades and collaboration with other sectors. Though the involvement of the private sector has proven beneficial for the quality of the service, the system of waste management in Frankfurt is still controlled by the municipality. The company and subsidiaries that provide the collection and disposal services (FES) are semi-public companies in which 51% of the shares are owned by the municipality. This ownership gives the municipality power over tariffs and waste management policies while allowing the company to function as a private enterprise [7].

The concept of reducing consumption is widely implemented throughout the environmental and infrastructure policies in Frankfurt. The emphasis on waste discrimination and reduction in consumption is evident in the educational programmes promoted by the city, raising awareness of the urban footprint and climate change. Consumption and the production of waste are reduced, while the reuse or repurposing of waste products is achieved through the introduction of new technologies and the involvement of several urban infrastructure sectors in waste management projects, e.g. cogeneration and composting. Furthermore, the development of cogeneration technologies has allowed the city to introduce a trans-sectoral vision in terms of the production of sustainable energy on the scale of a city district, reducing the amounts of waste products going to landfills as well as the need to bring in energy from outside the city boundaries.

4.4. Urban Agriculture for Environmental Protection

The urban agriculture sector in Frankfurt is directly dependent on the resources that the FrankfurtRheinMain Region provides. The municipality has developed a system of green infrastructure surrounding the urban perimeter called the *Frankfurt Green Belt*, which is

connected to other green spaces in the region, such as the *Regional Park FrankfurtRheinMain*. Within the Green Belt a multiplicity of uses for green areas coexist, e.g. urban parks, forestry, brown field redevelopment, agriculture, environmental protection and recreational areas. The *Frankfurt Green Belt* brings to the city biotic benefits related to species and biotypes as well as abiotic benefits related to climate, soil, water, and air. Likewise, the green infrastructure creates spaces for recreation, improved environmental qualities, and the generation of economic income from agriculture, forestry and catering industries [24].

4.4.1. Collaborative Approach for Green Infrastructure

Frankfurt's approach to urban agriculture requires the collaboration of different municipal departments as well as the Regional Authority. The *Regional Land Use Plan* (*Regionaler Flächennutzungsplan*) prepared by the Regional Authority establishes, among others, the areas for urban expansion, residential, industrial and agricultural use, as well as environmental protection [24]. The City Planning Department defines more detailed regulations for land use in the city, including specific planning instruments in order to minimise the impact of urban growth on the environment. In the same way, the Environment Department performs programmatic, educational and monitoring functions and is in charge of promoting programmes and projects to protect urban and rural green areas.

4.4.2. Impact of City Planning in the Urban Agriculture Sector

Land, whether urban or rural, is not a renewable resource and growing cities need to address the problem of urban expansion and growth in a sustainable way. Therefore, the city explores many variations of policies and regulations to reduce the impact of urbanisation on the natural environment while providing the necessary conditions for citizens to experience a high quality of life [22]. One example of policy innovation is the *Compensation Areas* policy, which includes different land use typologies, including protection of existing green areas and redevelopment. In this way, the policy covers not only agricultural land, but also the water and wastewater sectors, thus helping with the protection of water reservoirs and control of water bodies [25].

5. Characterisation of Infrastructure Initiatives in Frankfurt

The research and analysis of projects, programmes and activities implemented in Frankfurt within the main five sectors of urban infrastructure suggest three categories of initiatives, in accordance with the objectives and purpose of the programme or project. These categories are: practice-oriented, programmatic, and educational initiatives.

5.1. Practice-Oriented Projects

As the name suggests, practice-oriented initiatives are projects aimed at the provision of public services to residents. Evidently, a large proportion of the initiatives implemented in Frankfurt are categorised as practice oriented, since the main purpose of urban infrastructure planning is the provision of the necessary public services to sustain a good quality of life. Thus, the ambitious sustainable development visions adopted by the municipality have driven the different municipal departments towards innovative technological approaches to improve the efficiency of service provision in the city. The initiatives implemented in Frankfurt have a high degree of technological complexity, exemplified especially by the proliferation of projects in the renewable energy sector.

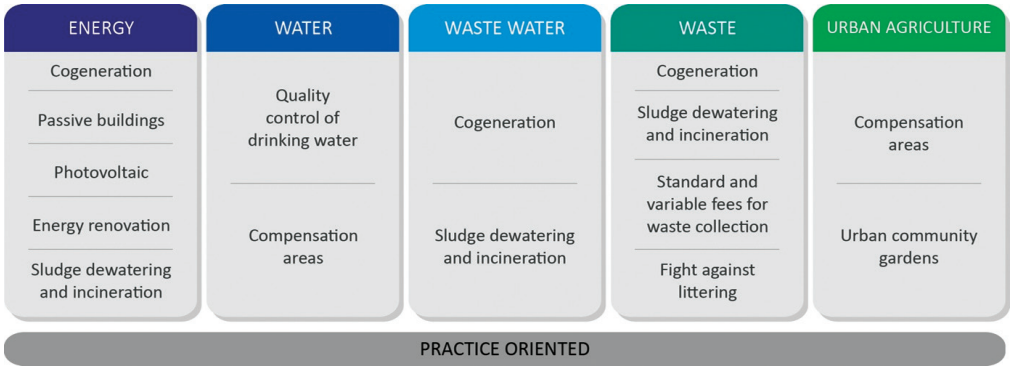

Fig. 5. Practice-oriented initiatives in Frankfurt (source: Global Urbanisation Research Team FRA-UAS)

The research results show an increasing number of projects in the energy and waste sectors. As a reason for the amount of projects in the energy sector, the research suggests rapid advances in technologies for the production of clean energies from renewable resources, along with the need for cities to reduce their ecological footprint. Reducing the carbon footprint requires changes in the production of energy by means of cogeneration, sludge incineration, and photovoltaics projects; reduced consumption through the promotion of passive buildings; increased efficiency in household appliances and industrial processes; and better housing insulation to reduce heating costs through energy retrofitting.

Similarly, the solid waste management sector is directly dependent on technological advances for the separation, recycling, and incineration of waste products, awareness of which has been created by the environmental policy in Germany. This collective consciousness, combined with a waste-collection fee based on product separation and individual needs, has resulted in less waste going to landfills and more efficiency in the waste management process.

For health reasons, the water and wastewater sectors are heavily regulated in Germany. In the case of water provision, the main projects are in place to protect the aquifers and water reservoirs from natural or artificial pollutants and to monitor the quality of water that reaches the end consumer. Therefore, there are few projects in this sector and they are very tightly

controlled by the Environment Department. In the case of wastewater, the challenge is in the effective collection, treatment and disposal of black water from households and industrial processes, and in promoting the reuse of rain and grey water for irrigation and non-potable purposes in households. Due to the high level of monitoring and control needed for the management of wastewater and the lack of this sector's attractiveness in terms of financial profits, the wastewater sector is 100% planned, implemented and monitored by public agencies; it is thus the only completely public sector in Frankfurt.

The urban agriculture sector is focused on promoting the use of non-developable green urban areas for the creation of community gardens. The main objective of the community gardens is to bring the local population together and raise awareness about environmental issues. Outside the city, the urban agriculture sector works in protecting agricultural land and balancing the loss of green areas inside the city with protected green spaces around the city such as the Green Belt and the City Forest.

Technological advances have played a crucial role in making sustainability policies feasible and facilitating the participation of different actors, from public to private and to citizens, in the provision of urban infrastructure with a focus on protection of the environment. The environmental focus is driven by the need to reduce consumption of natural resources, while shifting from the use of fossil fuels to renewable energies, as illustrated by the proliferation of energy-related projects and the evolution of waste and wastewater management processes in Frankfurt.

5.1.1. Semi-Public Companies for Public Service Provision

Trans-sectoral infrastructure planning and implementation requires the participation of diverse stakeholders and collaboration between municipal departments, along with a clear distribution of functions for the coordination of planning and execution processes. The research identified a specific collaboration scheme for the provision of public services in Frankfurt between the municipal departments and the private sector: while the infrastructure planning process is the responsibility of the municipality through the City Planning Department, the Environment Department and the Municipal Energy Agency, the operation of services and connection to the end user are often managed by semi-public companies that allow the municipality to control tariffs and ensure fair costs of public services. In order to retain control of the service provision, these companies are publicly owned with a minimum of 51% of shares held by the City of Frankfurt, but they are managed in a business manner, with the municipality having the main voice in the reinvestment of profits.

Service Operators

- Energy & Water: *Mainova AG – Stadtwerke Frankfurt am Main Holding Group*
- Housing: *ABG Frankfurt Holding Group*
- Waste: *FES – Frankfurt Disposal and Service Company*
- Wastewater: *City Drainage Frankfurt Company*
- Cogeneration: *Müllheizkraftwerk Frankfurt GmbH/AVA*

Fig. 6. Operational companies in Frankfurt

These semi-public companies are bringing efficiency and innovation to the city, as well as extending their scope

from one single sector to implementing trans-sectoral infrastructure provision projects such as the increasing joint collaboration between the energy and waste sectors. The use of new technologies for the production of energy from waste products is leading the trans-sectoral thinking in the city. These two sectors are showing increasing opportunities for collaboration and are even involving other sectors like agriculture in the trans-sectoral energy production process.

The wastewater sector is the only sector that is completely managed by the municipality through the public City Drainage Frankfurt company. Wastewater does not attract private investment and the federal and state regulations for the management of wastewater requires high degrees of control and monitoring, which is more feasibly achieved directly by the municipality. Sanitation and treatment of wastewater is crucial for public health and sustainable environments.

5.2. Programmatic Experiences

Programmatic experiences are the projects and programmes aimed at promoting behavioural change and sustainable practices within the city and among urban residents regarding the consumption of natural resources. These initiatives are found among every sector of urban infrastructure initiatives and are formulated by the different municipal departments, with specific policy objectives for each of the sectors. The scope of initiatives is broad: promotional programmes for the use of renewable energies, e.g. *Ökoprofit* [4, 17] and *Sensible Water Use* [20]; improving ecological performance in the private sector and obtaining profit from climate-friendly technologies; advisory services for businesses and social projects such as *Cariteam*; training the long-term unemployed population to become energy-saving advisors and assistants for low-income households [1]; and social projects such as *Ffmtipptopp*, whose aim is to improve cleanliness and have a social effect that enhances citizens' awareness and creates new jobs for the unemployed through training [8]. Municipal departments or agencies advise citizens and the private sector on infrastructure-related issues in order to achieve the ambitious sustainability goals proposed by the city, e.g. energy efficiency, reduction of water consumption, flood prevention etc.

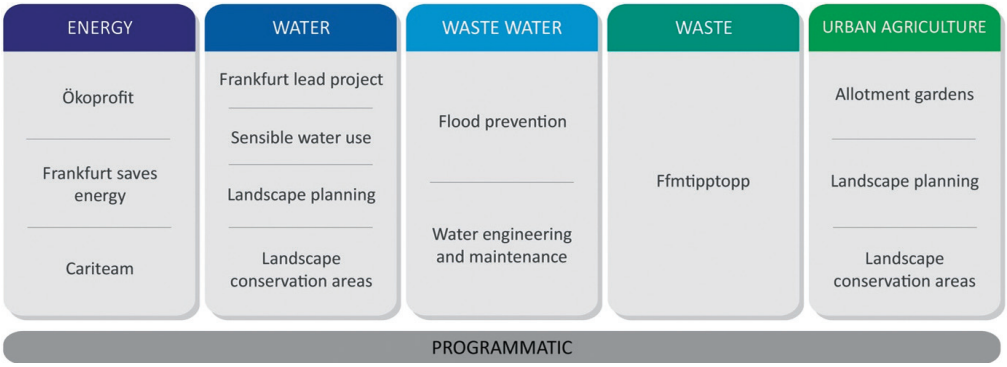

Fig. 7. Programmatic initiatives in Frankfurt (source: *Global Urbanisation Research Team FRA-UAS*)

5.2.1. Public Actors as Consultants for the Private Sector

The stakeholders involved in the programmatic initiatives are public departments and agencies focused on advancing the ambitious policy goals set by the municipality. Their responsibility is the formulation of policies, programmes and regulations in order to lead the city closer to achieving its sustainability objectives. The specific role of these public actors in the programmatic projects is to act as advisory boards to the City Magistrate and the City Council in the formulation of public policies, providing practical and professional feedback for decision-making. This advisory responsibility extends also to private investors and citizens in cases of urban development or building improvement.

The main municipal departments responsible for programmatic initiatives are the Environment Department, the Municipal Energy Agency, and the City Planning Department. These departments are in constant communication in order to plan and find opportunities for multi-sectoral collaboration, and to make urban development planning more efficient. Usually, the role of general programme coordinator is fulfilled by one of these three departments in accordance with the main characteristics of a given project, and it is this coordinator which invites the relevant stakeholders from other municipal departments or external actors from other infrastructure sectors to be involved in the project.

Programmatic Stakeholders

- Environment Department
- Municipal Energy Agency
- City Planning Department
- Building Construction Department
- Clean Frankfurt Office
- City Drainage Frankfurt am Main
- Health Department
- Green Spaces Department

Fig. 8. Programmatic stakeholders in Frankfurt

The Environment Department is intensively involved in the implementation of urban policies focused on environmental protection, with an essential role in the definition of regulations and the monitoring and control of the quality of the green infrastructures in the city, i.e. protection of greenery, agriculture fields and aquifers. It is also involved in the energy sector by raising awareness about the need for renewable forms of energy and the importance of climate protection in the city and the region. The emphasis of Frankfurt's public policy on sustainable development highlights the importance of the Environment Department as an advisory body as well as in the formulation of projects and programs. Therefore, the Environment Department is one of the most involved – both directly and indirectly – municipal departments in projects developed by all sectors of urban infrastructure.

The City Planning Department is the municipal organisation in charge of steering the urban development vision in the city, regulating the expansion, development and redevelopment of urbanisation, defining densities, plot coverage and heights, along with the urban requirements for each infrastructure sector. The involvement of the City Planning Department in the infrastructure sectors is indirect; its role resides in producing urban development plans with regulations and guidelines which are later used for the implementation of urbanisation and other development projects.

A common characteristic observed in these initiatives is the multi-sectoral collaboration approach; diverse municipal departments and agencies are involved in the infrastructure

planning process in terms of defining the regulations for land use, consumption of natural resources, and coordination of multi-sectoral programmes. Although most municipal actors are involved directly and are responsible for only one specific sector of urban infrastructure, the collaboration approach suggests their indirect involvement in programmes and activities outside their specific sector. In this sense, the research has identified a project-driven collaboration nature in the infrastructure planning processes in Frankfurt.

5.3. Educational Experiences

Educational or promotional experiences are focused on raising awareness and educating citizens in consumption-related issues, while promoting a sense of place and commitment to helping the city achieve its sustainability goals.

These experiences exhibit a strong sectoral approach and are generally developed by one municipal actor. These educational projects are mostly aimed at young residents, who later pass on their knowledge at home. The emphasis on educating young people requires easy-to-understand topics, therefore these projects, although they may have a trans-sectoral background, are usually executed by one single actor in order to facilitate their implementation. However, the education of the public has had a trans-sectoral impact in the consumption patterns of the population, resonating among the energy, water, wastewater and waste management sectors. This trans-sectoral impact has helped the city achieve milestones and partial goals in the reduction of resources, as well as transitioning from fossil fuels towards clean and renewable energies.

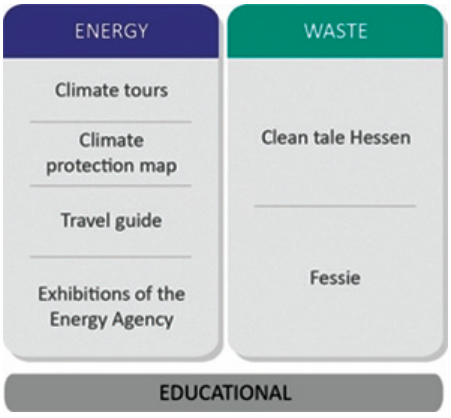

Fig. 9. Educational Initiatives in Frankfurt (source: Global Urbanisation Research Team FRA-UAS)

The responsibility of promoting sustainable urban development, clean energy, and reduced consumption starts with the City Magistrate and the City Council by enacting urban policies which direct the development of the city towards a more environmentally friendly approach. The municipal departments, i.e. the Municipal Energy Agency, the Environment Department, and the City Planning Department, are the three main stakeholders in the

implementation of sustainable urban policies in the city, and, as such, they have cooperated in bringing the city infrastructure towards new approaches which make the achievement of the ambitious goals of the city feasible.

6. Conclusions

The main programmes and projects in each infrastructure sector in Frankfurt highlight trans-sectoral planning practices within the city administration. These trans-sectoral practices have emerged from the need for coordination and communication between municipal departments. The analysis of Frankfurt's infrastructure sectors suggests that the concept of trans-sectorality in the city has been permeating infrastructure planning processes for years, thus resulting in a project-driven collaboration scheme. Depending on the specificities of a project or programme, the relevant stakeholders come together to design effective multi--sectoral approaches.

Trans-sectoral projects are becoming more necessary in order to achieve the environmental goals set by the municipality. Initiatives such as *Master Plan 100% Climate Protection* and *Frankfurt Green City* approach look at urban development in a holistic way, involving different sectors of society through public-private partnerships, engagement of private actors, and operational stakeholders as semi-public actors. The diversity of stakeholders is complemented by a multi-sectoral approach that involves two or even three urban infrastructure sectors for large infrastructure projects. For example, in the energy sector projects are looking at utilising waste products and biomass and reducing the consumption of natural resources, i.e. by cogeneration from household waste and sludge from wastewater treatment. These energy projects demand trans-sectoral collaboration between the Municipal Energy Agency, the City Planning Department, the waste management company, and community organisations in the case of by-products from cogeneration that are used for compost.

Moreover, when examining the experiences in Frankfurt, it can be observed that the energy sector leads the implementation of environmentally friendly projects; however, the Municipal Environment Department and the City Planning Department are also involved in most urban infrastructure projects and sectors, either as advisors, coordinators (as is the case of the Municipal Planning Department for large infrastructure projects), or monitoring and controlling the quality of the environment and the products delivered by the infrastructure projects.

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Three proposals for the reconstruction of the Eagle Pavilion in the Branicki Garden in Białystok – designs, method selection and execution

Trzy koncepcje rekonstrukcji pawilonu pod orłem w Ogrodach Branickich w Białymstoku. Projekty, wybór metody i realizacja

Abstract

This article describes three reconstruction designs for the Eagle Pavilion (Pawilon pod Orłem, trans. by author) developed by three architects at different moments in history and created using different methods in accordance with the technical means available at the time. The article presents a comparative analysis of the methodologies applied with these designs with regard to the context of the historical accuracy of reconstruction. In the conclusion of the article, I refer to the dilemmas related to the justification of restoring historical objects understood as the reconstruction of historical space, as well as the risks of conveying improper meaning that bears the appearance of authenticity.

Keywords: reconstruction, heritage buildings, architectural conservation

Streszczenie

Przedmiotem artykułu są trzy projekty rekonstrukcji Pawilonu pod Orłem, opracowane przez trzech architektów w różnych przedziałach czasowych, realizowane przy użyciu różnych metod w zależności od dostępnych środków technicznych. W artykule przeprowadzona zostanie analiza porównawcza zastosowanej w nich metodologii w kontekście wiarygodności historycznej rekonstrukcji. W konkluzji artykułu odniesiono się do dylematów związanych z zasadnością przywracania dziedzictwa w formie szeroko rozumianych rekonstrukcji zabytkowej przestrzeni i związanych z tym niebezpieczeństw błędnego przekazu noszącego pozory autentyczności.

Słowa klucze: rekonstrukcja, zabytki, konserwacja architektury

Fig. 1. Eagle Pavilion, Białystok: fragment of an engraving by Rentz and a view of the current state following the reconstruction of the gazebo

1. Introduction

Reconstructions of buildings that have not survived, as well as the recreation of forms, massings and architectural details on the basis of preserved relics and source materials, were developed in the past using various graphical techniques, or in the form of mock-ups, with various digital technologies that have recently entered use. Visual reconstructions serve not only as a cognitive purpose, but – developed into the form of a construction--phase design – can become a basis for future development projects. The subject of the

article is a collection of three designs for the reconstruction of the Eagle Pavilion located in the garden salon of the Branicki Palace in Białystok. The designs were developed by three architects in different time periods, with the use of different research methodologies and design tools.

Białystok's residential complex, called the Polish (Podlachian) Versailles[1] [3] across Europe in the eighteenth century, owes its construction to Jan Klemens Branicki, who had been expanding the residence up to the end of his life and left it unfinished. Its gardens, based on an axial, multi-directional geometric layout compositionally subjected to the palace and linked with it through a shared ideological programme, were an essential element that enhanced its splendour. The composition of the garden had a two-level layout, with a division into an upper and a lower section. The upper terrace featured the parterres of the garden salon, comprised of eight embroidery-type beds with boxwood patterns. This section was delineated by a canal and ponds from the northwest and by a tall wall of rows of linden and hornbeam trees, creating a bosquet from the southeast. The upper terrace was enclosed by a stone balustrade with fountains and sculptural decorations; from the side of the canal, the central perpendicular axis culminated in the openwork gazebo of the Eagle Pavilion that towered above the parterres (the name was derived from a sculpture of a gilded eagle that topped its dome) [4].

We can read the following about the pavilion in the inventory of the entire property written in 1772 after the death of Jan Klemens Branicki: "A treillage gazebo from (…) the side of the garden, with four arcades painted in a green check pattern, on whose surface, facing front from the garden, there is timber trophy of arms painted white, and near it, to its sides are two wooden antiques, gilded. A small timber vase above the trophy of arms, carved and gilded. A descending eagle at the top of the gazebo – made from timber, gilded, carved. Its surrounding floor is made of stone, with four wooden benches surrounding it, covered in stone near the arcades, with two stone steps inside, a wire grate on four of its corners, in poor condition, for birds. A porch is around it, with a stone floor, surrounded by an iron grate. Descending downwards from the gazebo to the lower garden are two sets of stairs, with stone on both sides, upon which there is an iron grate, underneath, along the stairs, placed on the stone. There is a small cascade underneath this gazebo, which stretches all the way to the lower garden, reinforced with stone. A Neptune of stone, placed in a wall, carved, meant to let water from underground – from the fountains – into the canals in the lower garden. The gazebo stands on a masonry base, which is boarded, on the side where the treillage gazebo is placed there runs a stone balustrade, painted white, on a masonry base (…)" [2, p. 246].

After Jan Klemens Branicki's death, his rich legacy of manuscripts, extensive correspondence and other important sources (itineraries, lists, receipts for completed works, etc.) was divided and scattered. The primary source for recreating the appearance of Branicki's Białystok residence is the fragment of the inventory list from 1771/1772 quoted above, which is stored in the Central Archives of Historical Records in Warsaw, in the archive section of the Potocki family from Roś. Branicki's private correspondence concerning construction and

[1] Naming issues are discussed by Jan Nieciecki in the article *"Polish Versailles" – Białystok of Jan Klemens Branicki*.

artistic projects is also located here. Numerous mentions of the Białystok residence can also be found in period texts such as guidebooks, memoirs and reports by travellers who relayed their impressions – full of amazement – of the palace and its surroundings. The urban layout of the city and the residence is displayed on a small number of preserved plans from the second half of the eighteenth and the beginning of the nineteenth century, with the palace's external appearance, as well as that of its garden furniture (pavilions, fountains) found in iconographic sources from the collection of Stanisław August; this is stored in the Engravings Office of the Warsaw University Library. A series of copper engravings that document the appearance of the garden, commissioned by Branicki and made by Michael Heinrich Rentz on the basis of drawings by Jan Henryk Klemm, is of very high epistemic value. We know of four views stored at the Princes Czartoryski Museum in Krakow and one copper engraving in the collection of the Medical University in Białystok. The collection of the Bibliotheque Nationale in Paris features four drawings made by Pierre Ricaud de Tirregaille, a French architect and engineer, a specialist in water systems, who was hired by Branicki in the years 1752–1757. These depict a view of the courtyards in front of the palace, a view of the upper garden, a fragment of the garden with a Chinese gazebo and a small palace on Wysoki Stoczek [6]. Another important source is a collection of photographs from the period of the First World War and from the 1930's and 1940's, collected in the so-called Glinka's Files[2] [7].

2. Comparative analysis of three design proposals

Based on an analysis of source and iconographic materials, the Eagle Pavilion is a spacious gazebo with a treillage structure that was used as an aviary in Branicki's times. The upper part of the pavilion, situated at the level of the garden salon, was a timber structure with a square-based plan, crowned with a latticework dome with a sculpture of an eagle on its top. The part of its ground level that was accessible from the lower garden had a masonry structure with a wall fountain (cascade) on the frontal wall which directed the water from the fountains to the canal. The upper and lower sections were linked with external stairs. The gazebo was painted green, the colour providing a background for the remaining decoration. The sculptural decoration was gilded (busts on corbels flanking the entrance from the side of the garden salon and the crowning sculpture of a descending eagle), the 'armature', which probably meant the trophy of arms on the tympanum, was painted white, with the latticework possibly also being white.

In 1946, the Chief Office of Museums and the Preservation of Historical Monuments commissioned arch. Stanisław Bukowski to design the reconstruction and adaptation of the former Branicki Palace into a people's culture palace and regional museum. The design was developed on the basis of guidelines by the General Heritage Conservator at the time, Prof. Jan Zachwatowicz, as well as on the basis of studies by the art historian Jan Glinka. The main

[2] Glinka's Files was classified by Prof. Teresa Zielińska, who works at the Central Archives of Historical Records in Warsaw.

conservation objective was to reconstruct the palace with regard to its form and architectural features from the middle of the eighteenth century, with the removal of alterations from the nineteenth century that had been made by Tsarist authorities. Work began in the 1950s on a design of the restoration of the garden complex, authored by Prof. Gerard Ciołek. The garden architecture design, including the completed designs of the Italian Tuscan pavilion, the retaining wall of the upper terrace and the bridge, as well as the design of the Eagle Pavilion that was not put to use (dated to 1950), were prepared by the architect Stanisław Bukowski. The second design for the reconstruction of the gazebo, which was also not put to use, was developed by the architect Jerzy Tryburski in 1971. Both documentations are kept in the archive of the Podlachian Voivodeship Conservator of Historical Monuments in Białystok. The third proposal for the reconstruction, which was completed in the years 2009–2011, was prepared by the author of this article. The three documentations, despite being largely based on the same input data and source materials, differ significantly because of the different approaches to reading them, particularly in terms of the fundamental dimensions of the building, the proposed construction technology and the architectural details.

The design of the reconstruction of the gazebo developed in around 1950 by the architect Stanisław Bukowski featured a building on a square-shaped plan, with a 7.30 m long side, with a single storey and a height of 12.40 m, with a single-space interior covered with a flat deck supported by timber beams. In Bukowski's proposal, the pavilion had a masonry structure, with walls that were 58 cm thick, covered by a dome (featuring a timber structure), clad with metal sheets and panels imitating treillage. It had facades divided by two pairs of Corinthian pilasters supporting an entablature, with an arcade entrance from the side of the garden salon, accentuated with a triangular jerkinhead topped with a vase, with the panels between pilasters filled with a wooden grate imitating treillage. The pseudo-latticework dome covering the pavilion was crowned by the sculpture of a bird (an eagle) on top of a sphere. The tympanum above the entrance was decorated with trophies of arms, the frieze of the entablature was decorated with rosettes, while the intermediate panel of the dome was adorned with festoons. In the interior, at the height of the column heads and below the ceiling, there were profiled parapets that encircled the space.

The design by the architect Jerzy Tryburski was developed in 1971. The building was designed on a square-shaped plan, with a side of 7.24 m long, with a single storey and a height of around 12.30 m with a single-space open interior, with arcade openings in its four walls. As was the case with the previous proposal, a masonry building was designed with 62-cm-thick walls. In this version, the pavilion was covered with a concrete floor slab and topped with an openwork dome made from wooden laths and of an unspecified structure. The articulation of the facade was designed in the Doric order with openings between pilasters filled with a wooden latticework and the entrance at the axis of the facade topped with a semi-circular arch. The facade from the side of the garden salon featured a triangular jerkinhead topped with a vase. The tympanum was filled with trophies of arms, while the latticework dome was decorated with pelmets featuring swags and was topped with a sculpture of a bird (an eagle) on a sphere. The arches of the entrance openings featured decorative zwickels, while the frieze of the entablature featured rosettes and the intermediate panel of the dome was decorated

with festoons. The interior walls were encircled by a profiled parapet. The floor was made from square-shaped sandstone tiles.

The third conceptual design proposal, which was completed in the years 2009–2011, was designed by the author of the article. The building was designed to feature a square-shaped plan with a 5.40 m side, with a single storey and a height of 8.50 m, a single-space interior and arcade openings at the axes of its four walls covered with a latticework dome. In contrast to the other proposals, a timber pavilion was designed with a reinforcing steel structure. Its covering was designed in the form of a timber latticework dome with a bell-like cross section, the band of its base is decorated with an ornamental festoon, with the dome being topped with a lambrequin at the base of a sculpture depicting an eagle with its wings spread out sitting on a sphere crowning the entirety of the structure. The facades were divided with pairs of Doric pilasters, supporting an entablature with rosettes featured on a frieze. The frontal facade from the side of the garden salon was accentuated with a triangular jerkinhead topped with a vase, while the structure's tympanum was filled with trophies of arms. The zwickels above the arcade of the entrance feature floral ornaments with busts on corbels placed on the lateral axes. Inside, at the height of the entablature, there are profiled parapets that encircle the space. The floor is made from sandstone tiles.

The three documentations, despite being largely based on the same input data and source materials, differ from each other due to different approaches to reading them, particularly in terms of the main dimensions of the structure, the proposed construction technology and the architectural details.

2.1. Architectural form, conceptual design of the massing

Upon comparing the architectural form and massing of the structure, we can observe that the three proposals are similar in terms of proportions, which is as a result of properly reading the relevant engraving. The slight differences are the result of the different approaches to detail.

2.2. Structure, material, technology

We can observe significant differences in terms of the gazebo's structure. The first and second design featured masonry walls, while the third gazebo is made from timber with steel structural elements. The structure of the decks is also different: Stanisław Bukowski designed a deck supported by timber beams, Jerzy Tryburski proposed a concrete vault, while the third proposal adopted a partial covering with a coffered ceiling supported by timber beams and leaving the openwork wooden dome visible.

2.3. Building techniques and aesthetic

In the proposal by Stanisław Bukowski, wooden laths imitating treillage were placed directly on the walls and the covering of the dome. The designer did not include true latticework openings in the spaces between the pilasters and on the dome, which is why the structure did not give the impression of the lightness of a latticework gazebo. In the design by Jerzy Tryburski, the

openings between the pilasters are filled with a latticework grate, with the dome also featuring latticework. This proposal is definitely closer to the concept of treillage gazebos.

In the third proposal, a different principle for constructing the aesthetic of the building was proposed, along with a structure with a fairly significant amount of latticework elements. Timber treillage pilasters were designed, with the spaces between them filled in with latticework screens. The dome was given a similar treatment as its latticework can be seen both from inside and outside of the gazebo.

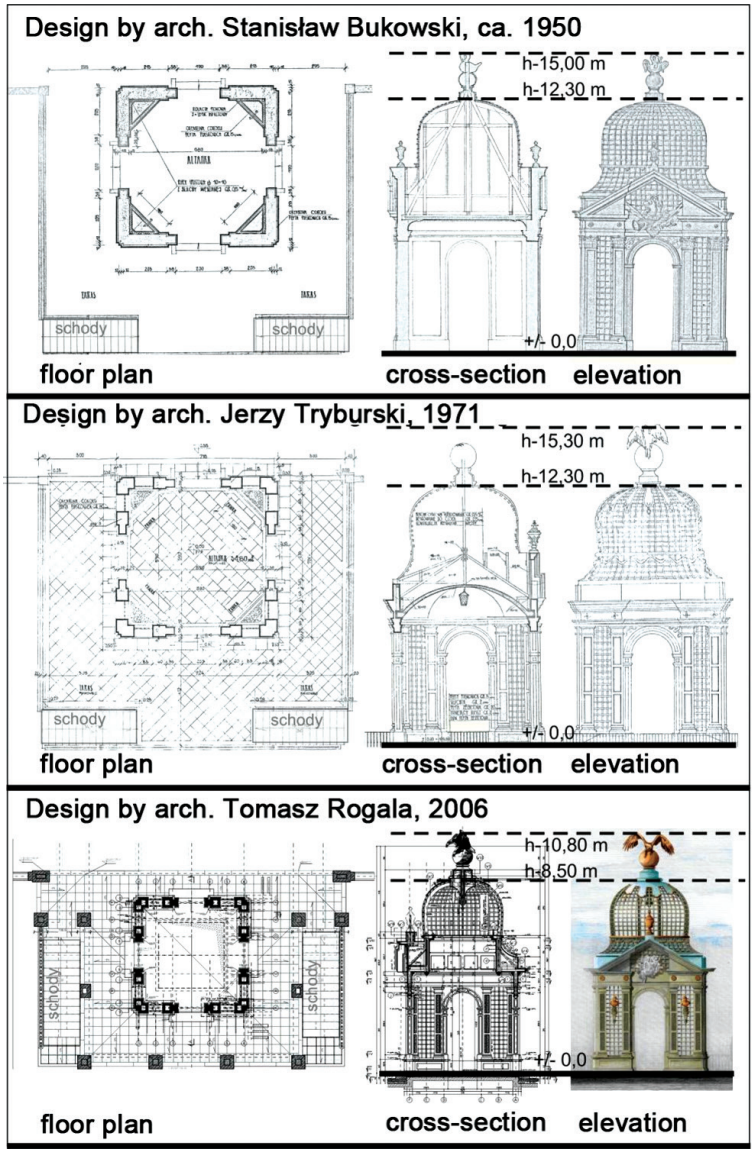

Fig. 2. The Eagle Pavilion, Białystok: comparative analysis of the form, structure, technology and aesthetic of the building

2.4. Dimensions and spatial layout

The most significant differences between the proposals can be observed when comparing the scale of the structures. The first two proposals differ only slightly from each other, and there are significant differences observed when compared with the third:

- The differences in the dimensions of the plan of the gazebo amount to 190 cm and 184 cm (between proposals 1 and 2, respectively, and proposal 3).
- The differences in the height dimension of the gazebo, measured to the base of the eagle, amount to 390 and 380 cm (between proposals 1 and 2, respectively, and proposal 3).
- The differences in the height dimension of the gazebo, measured to the top of the eagle, amount to 450 and 420 cm (between proposals 1 and 2, respectively, and proposal 3).

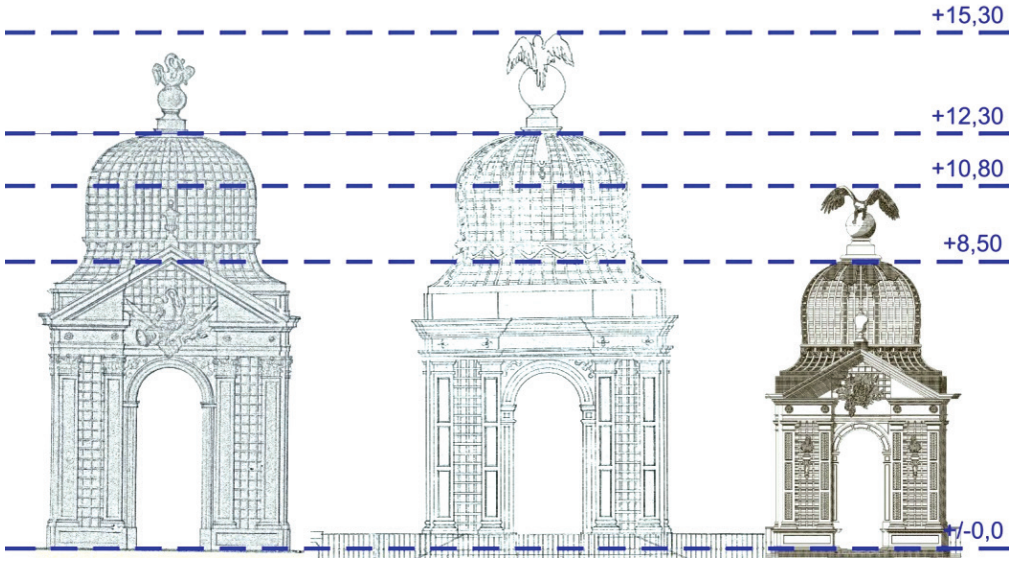

Fig. 3. The Eagle Pavilion, Białystok: comparative analysis of the size of the gazebo as proposed in the three design proposals

The comparative analysis of the three documentations presented above leads to the question as to the design methodology that was employed and the historical fidelity of the proposals and presents problems associated with working on developing the reconstruction hypotheses, particularly under conditions in which there is only a negligible amount of authentic substance or a complete lack thereof. The first documentation is dated to the period of the intense reconstruction of heritage buildings after the Second World War. The second period is the 1970s, with the development of the third design coinciding with a period of development of digital technologies and an evolution of research and design tools, which has caused significant changes in the methods of work employed by architects, heritage conservators and architecture historians. The effects of these three designs are completely different.

3. Research methods and their use in the design of the pavilion's reconstruction

One of the elements that guarantee proper reconstruction is the analysis of written and iconographic sources, as well as their up-to-date interpretations. New studies concerning the authenticity of documents and their dating are constantly appearing, while technological progress in image processing has made it possible for us to obtain a greater amount of precise details, which, in the case of iconographic material, is of fundamental importance. We do not know what quality of iconographic material had been at the disposal of Stanisław Bukowski; however, based on his design, we can see that he erroneously read the orders of the pilasters and ignored a portion of the sculptural decoration. Jerzy Tryburski had probably had a better copy of the engraving as the order of the pilasters and the sculptural decorations in his design were the same with those on the engraving.

The development of the global Internet network has made sharing, storing and conducting studies – as well as access to archival materials and documentation – much easier as we can familiarise ourselves with the catalogues of the largest libraries without any restrictions, which is why I had at my disposal almost the entirety of the available iconographic material and the ease with which one can currently search for structures for comparison undoubtedly gave me an advantage over the authors of earlier designs.

3.1. On-site research

The basis for developing proper reconstructions are diligent on-site studies. Archaeological work from 1997 performed by Prof. Andrzej Kola did not result in obtaining the expected information. "It was not possible to delineate the outline of the footing section of the Eagle Pavilion gazebo… its remains, if any, were either covered or destroyed during construction work meant to reconstruct the gazebo that had been performed here over a decade ago" [1, p. 57].

3.2. Study of the pavilion's geometry

The greatest amount of data concerning the pavilion's geometry was provided by digital analyses of iconographic materials featuring the architecture of the pavilion along with a restitution of the space of the garden salon.

Iconographic materials in the form of drawings, photographs and graphics do not contain specific information describing the geometry of architecture. This is why analysing a space on the basis of a two-dimensional drawing or photograph necessitates the search for a three-dimensional form of the building that will enable a more precise display of its geometric properties.

One of the methods of determining the shape of a form is an analysis that utilises the properties of perspective projection. Sketches, floor plans, cross sections and facades prepared in this form in relation to the entire massing or individual details can become a basis for preparing either a traditional or a virtual model. Such a recreation of architectural elements makes it possible to understand the proportions or mutual dependencies between each

element, but it does not always provide definitive information concerning the dimensions of a building or its location.

When defining a building, we must start by determining its location. It is typically defined as a space, the base of which is equivalent to ground level. The location of the building on a drawing is not always legible, but elements that indicate its placement can be present (surfaces, walls, roofs, paths), forming distinct markers which make it possible to perform the first analyses of the space of a two-dimensional drawing. The mutual spatial linking of these distinct elements (markers) can be connected into a cohesive whole, e.g. a digital 3D drawing.

Another part of architectural space analysis is its interpretation on the basis of recreating the process of the construction of a building, which we can currently perform by building a three-dimensional model (either a digital or an analogue model). The reconstruction of a building that does not physically exist requires the interpretation of the collected material, adding commentary and description to it and identifying the most significant phases that the process was composed of.

The interpretation and analysis of materials concerning the Eagle Pavilion took place in the phases described below.

The first phase was the analysis of drawings and sketches and a review of the literature and ongoing studies. This stage featured the identification of reference objects, which made it possible to search for references and interpret the form.

The second phase was an analysis of the proportions and interdependencies between the pavilion's individual elements in relation to the palace and the garden complex (Fig. 4a). This made it possible to create a three-dimensional layout of reference points (markers) and mutual linkages, presented as the third phase. During this stage, a detailed analysis of proportions, shape and location was performed, using the coordinate system of a previously prepared grid based on a survey map (Fig. 4b). The data concerning the perspective projection parameters obtained in this manner (e.g. observer location) made it possible to obtain side views of the surfaces of the facade and the floor plan and compare the pavilion geometry with earlier geometric constructions (Fig. 4c).

The fifth phase was the drawing of architectural details and decoration (Fig. 4d).

The sixth phase was the verification of mutual linkages and the correctness of the elements, the removal of errors in the structure of the entire model and making the final architectural model along with the construction documentation and visualisations (Fig. 4e). Digital visualisations were of a form that presented the results of the virtual reconstruction process and served as a tool for the verification of the correctness of the design documentation. The presentation of the architectural drawings, due to their high degree of detail, does not provide a complete image of the building being designed, while the presentation in the form of images or animations makes it possible to see the design as intended by the author.

The seventh phase was the stage of the construction of the pavilion (Fig. 4f).

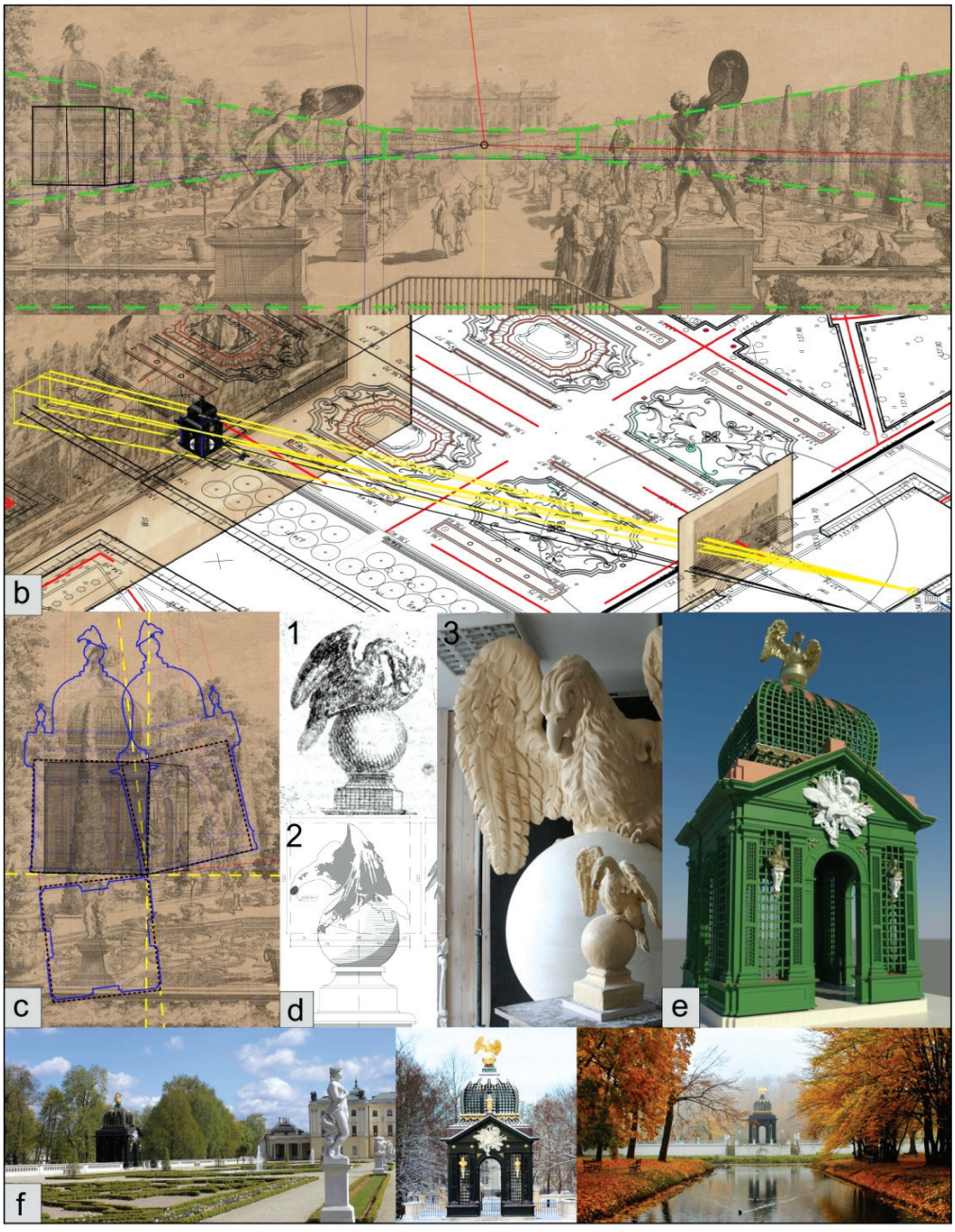

Fig. 4. The Eagle Pavilion, Białystok: a) selected example of the analysis of the height of the pavilion relative to the height of the bosquets and palace facade parapets, b) digital 3D analysis of the placement and proportions of the gazebo on the basis of a survey map and an engraving placed in various projection planes of the plan, c) geometric construction of the gazebo's facade plane rotations, d) sculptural decoration: 1. the drawing of the eagle from Rentz's engraving, 2. drawing of the eagle from the design, 3. model of the eagle made to a scale of 1:10 and 1:1, e) gazebo 3D model visualisation, f) completed project

4. Conclusions

The example of the different reconstructions of the same building, prepared on the basis of similar source materials, demonstrates how work methods have evolved and how different the final result can be, in addition to how important it is to maintain restraint and responsibility in the preparation of reconstruction projects. It is essential to not treat earlier graphical hypotheses as equal to sources and to maintain an appropriate distance, particularly when the buildings that are to be reconstructed have not survived or when only a small part of them has survived. The use of reconstructions that were based on erroneous assumptions resembles a vicious circle, where the start is an improper reconstruction of one structure or detail that is used for further comparisons, resulting in subsequent erroneous documentation. Another significant threat is the transfer of poorly thought-out reconstructions to construction projects.

The entire responsibility for the later appropriate use of graphical reconstruction rests with its authors. It is key to properly define what is the documentation of a building, what is a documented hypothesis and what is the author's own design. It would be appropriate for the predominant part of a documentation to be composed of the documentation covering the study of hypotheses, and for the graphical reconstruction itself, to responsibly point to the possibilities of further study and interpretation and be a reliable research tool.

The dynamic development of digital technologies and the evolution of research and design tools leads to changes in work methods, providing architects, conservators and architecture historians with new opportunities and making it possible to recreate the historical appearance of historical structures. This is typically simplified as the final visualisation of the structure, being its attractive presentation, while the fundamental question is the historical fidelity of the reconstruction, which can only be obtained through proper methodology utilising the experiences of scholars from various disciplines. By comparing the three designs in this article, I wanted to direct the readers' attention to the necessity of critically interpreting earlier documents and the possibility of using contemporary research techniques and tools in synergy with traditional methods during the individual stages of the process of the reconstruction of historical space.

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The use of 3D computer graphics to preserve, reproduce and obtain information relating to a historically valuable object

Zastosowanie komputerowej grafiki 3D do zachowania, odtwarzania i pozyskiwania informacji oraz wizerunku historycznie cennego obiektu architektury

Abstract

This paper provides a summary of the benefits of 3D computer graphics for preserving, reconstructing and obtaining information pertaining to historically valuable architectural objects. The current technology is discussed including its most common applications and examples of solutions as well as the creative process of three-dimensional architectural modelling.

Keywords: 3D modelling, 3D graphics, digital reconstruction

Streszczenie

W artykule przedstawiono zastosowanie modelowania przy pomocy komputerowej grafiki 3D w celu pokazania korzyści płynących z wykorzystania tej metody w zachowywaniu, odtwarzania i pozyskiwaniu informacji wraz z wizerunkiem w kontekście historycznie cennych obiektów architektury. Omówiono aktualną technologię z jej najczęstszym zastosowaniem wraz z przykładami rozwiązań i procesem twórczym trójwymiarowych modeli architektury.

Słowa kluczowe: modelowanie 3D, grafika 3D, rekonstrukcja cyfrowa

Technological developments in the field of 3D graphics and computer-aided design have increasingly provided us with new tools for creating virtual representations of real-world objects. The ongoing nature of these technological developments continues to present us with new opportunities in almost every area of everyday life. The dramatic increase in the quality and quantity of knowledge available to us creates new potential with regard to artistic creativity, industry and science.

While discussing 3D modelling, we must regard it as a creative activity which can essentially be described as a mathematical representation of an object's surface in three dimensions by means of an appropriate software program. Depending on the software and what the given material is intended for, the current array of options is very wide. Many opportunities are available, but there are also limitations at the expense of the enhanced efficiency. This is related to the problem of the specific skill-set specialisation for a given task. Each program, like any other tool, requires a different approach and competence to operate it. The technique of creating models by sculpting, spatial drawing, manipulating forms, and generation by the means of parameters or any other aid from which the models are created requires a proper file format. This, in turn, introduces the problem of the accessibility of records for prospective recipients, and how a given digital material may be used in the future. With the constantly changing reality and technological progress, the creation of digital data records in a universal format, along with the accessibility to materials, may require either the implementation of certain rigid outlines or the establishment of specially designed projects. There is the possibility of transmitting data between different programs, but it is done with a certain amount of effort and sometimes it causes a loss in the value of the material. Despite these slight deficiencies, the ongoing process of program specialization has immensely contributed to the incredible achievement in the field of three-dimensional modelling.

How exactly does 3D modelling serve architects, historians, archaeologists and other researchers? It is an undeniable fact that spatial changes are taking place over time and are inevitable and indeed natural, whether it is due to natural, random, deliberate or human activity. Recognition of existing changes and the ability to understand them in the best way to excel in digital reproduction. At present, new potential is brought in the field of archiving and reconstructive projects with regard to monuments conceived in an alternative virtual space. It is what can be defined as a kind of timeless protection or preservation of information regarding the state in which the object was situated at a given time, or a way to obtain that kind of information.

There are numerous methods of creating copies of an object. They differ in the details and information resources they contain and each method has its own advantages and disadvantages. Depending on the established work organisation and the technological method, the digital record can be executed as either a comprehensive form which reflects the main parameters and substantial information about the object or a one-to-one virtual copy. The latter is achieved by using a highly detailed information recording process, which requires a sequence of diverse virtual replication techniques such as precise analytical research of the subject, this in turn enables creation of an almost perfect copy. Of course, the more information and quality is incorporated, the greater the expenses are, including the time required and the usage of hardware resources.

The basic of 3D modelling of existing buildings relies mainly on the transfer of a given object's reference points from the real world to the virtual world. The mapping of these points and their

coordinates in the Cartesian scale occurs in numerous ways; from old-fashioned walking with a measure and noting down measurements, through to the simultaneous work of reading an object's data, creating a spatial model and then applying methods of tacheometry, photogrammetry and algorithms which are able to generate a virtual object based upon the received visual material.

Work based on BIM deserves proper recognition. Building information modeling involves the work based on parameters, blocks, values, attributes and other important information. All data are collected together in a single file which allows to generate up-to-date information after any changes are applied to 3D model. Moreover, a digital entity created in this way becomes a valuable tool for use in other types of work. An example can be a scan made with the aid of the BIM method for an inventory. The scanned object was the front elevation of the Cadet School in Krakow made by the academic staff of the Cracow University of Technology and a representative of the BIMPOINT company [8].

The protection of architectural heritage through 3D modelling does not have to rely solely on the process of transferring the reality that surrounds us as it can also be used as a tool to acquire knowledge about the past and attempt to better understand it. In order to create the virtual speculative duplicate as accurately as possible, the digital reconstruction of a previous state of building or a building that no longer exists, requires an appropriate approach and suitable research procedures. The mere transfer of monument to a virtual space is not sufficient, what is required is reference to the relevant critical discourse present in the field of history. Sometimes, however, it calls for the aid of a wider range of scientific tools. The studied historical materials should, and even must, be regarded in terms of contextual, historical processes, which is broadly understood as a methodology of history. The theoretical aspect of this topic had been extensively discussed in the book of the Polish historian Jerzy Topolski entitled *Methodology of History*. The skills of decoding are of key importance in this situation. In every field, relevant knowledge and expertise of the 'symbol system' and the 'language' of the transcribed material is essential. In architecture, this is knowledge of reading plans, drawings, illustrations and descriptions that use building terminology, although it may not be sufficient itself when in contact with the form of 'old language'[5].

Depending on the available material, reconstructions differ. During 3D modelling process, the very method of analysing source material can evolve. Thus the whole process in the manner of asking questions about information in material changes. The analysis of visual materials for decoding information requires not only skills, but a variety of methods. For example, getting the proportions right can be achieved simply by measuring the length of the given building in a visual material and next by mathematical calculations convert the dimensions to the appropriate scale. However, the process can sometimes be considerably more complex. For example, one can identify the correlation between the length of the shadow, or by means of descriptive geometry, a common denominator on the scale of perspective depth. As has already been discussed, in the case of an existing object, methods including photogarmmetry, which allow determination of the coordinates of points that include a great number of different pictures of the architecture in development, provides the opportunity to not only reproduce but even generate a model with help of appropriate software. It often happens that there is no access to sufficient visual materials, which forces one to use a wider range of information and supplement

it with identical cases or corresponding realities in the context of the location and architectural history. This may often lead to a kind of historical narration. For example, in the case of the Palace of the Vatican Ambassador in Valencia, where the task was reconstructing the now non--existent building in the Gothic and Renaissance style, researchers used assembled historical, literary and graphic materials, as well as information obtained from archaeological remains. The basic materials were preserved demolition records along with old drawings and a map of Valencia. This served as a means of determining the exact location of the object and helped identify its architectural features. Unidentified components had been determined and inserted on the basis of information obtained from other similar buildings by the means of analytical deduction. Consequently, the historical object was recreated and 'preserved' in two styles [4].

For archaeologists, 3D modelling has become one of the most important tools for working on substance of momentous significance. Digital equivalents enable the conducting of research without interference to the original substance and even run virtual simulations that aim to resolve queries or pose new questions. Just as in other cases, works of ancient architecture which are based upon digital reconstruction are rooted in original sources as well as derivative sources and educated guesswork. Despite, the greatest effort and desire, some things remain the subject of speculation with regard to their actual state. This only confirms the key statement that the obtained image is not an absolute fact. This notion was most accurately described by the English archaeologist and historian Simon James who said: "Every reconstruction is wrong. The only real question is, how wrong is it?".

Another example where 3D modelling was employed is the reconstruction of the Royal Palace in Lobzow. The building functioned as the Cadet Institute for the Austro-Hungarian Army. Currently, it serves the Cracow University of Technology. The state of this object prior to the Austrian reconstruction is little known. By consulting the surviving records of reconstruction and depictions drafted by contemporary artists, an image of this historical object was created. By analysing all data and subjecting them to the comparative process along side with the model, it was possible to find issues never before considered. Currently the model serves as the basis for comparison in further research regarding the appearance of the building in earlier times [6].

The practical application of materials in the form of virtual models of architecture can already be observed. They are incorporated in museum exhibitions, which in turn affects education, tourism and increases social awareness on issues such as transience and cultural identity by means of 'architecture in time'. Cultural improvements have global scale impact and are groundwork for further progress. According to Professor Jerzy Topolski, all endeavours of this sort are meant to contribute to the advancement of humanity, which would not have been possible without social organization. Organization which is built upon insight in social reality and the awareness of the history. An example is the Virtual Archaeological Museum of Herculaneum. The CyArk organisation is worth mentioning here as its volunteers are creating a library of three-dimensional models of forms which are invaluable not only for posterity but also as an aid for conducting comparative studies concerning the visual aspects of buildings.

The creation of 3D computer-generated models is an efficient way to understand the state of a given monument, and the process of its ongoing changes over time. The discussed creative process aided by the means of digital modelling techniques is in fact, a constant

decision-making process. One must make decisions regarding each aspect of the building and its surroundings. The search for co-dependencies in construction opens up a vast array of possible solutions and poses new thought-provoking challenges. Even the rudimentary reconstruction of an object provides a new perspective for the already collected previous data. It helps in a distinct process of analysis and the deduction of a speculative form of the given monument in a specific time period. The constant development of technology offers increasingly compelling means of experiencing virtual objects and the prospect of realising them at a reduced scale through the use of three-dimensional printing. The advancement of the field of printing technology now makes it possible to print buildings at a micro-scale. In the future, this will facilitate the reconstruction and reproduction of objects at their original size. Moreover, products developed by the means of 3D modelling can serve as a valid source of information for the next generations and be a reliable tool of 'eternal protection'.

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The difficult heritage. The reuse of former prison buildings

Trudne dziedzictwo. Ponowne wykorzystanie dawnych budynków więziennych

Abstract

In recent years, there has been a trend to reuse abandoned buildings. Adaptive re-use allows preservation of the original structure and implements a new function to it. Suchactivity could help to preserve the historic value of buildings; moreover, many other advantages can be found in educational, ecological and economic fields. However, the question arises of whether every object can be freely adapted. This article examines the case of old prisons which have, for instance, been adapted into hotels and museums. Knowledge of the history of prison architecture as well as experience in preserving and adapting prisons could help to identify the appropriate function for the abandoned penitentiary facilities.

Keywords: heritage, architecture, prison, adaptive re-use, penitentiary architecture, correctional facility, panopticon

Streszczenie

W ostatnich latach zauważalny staje się pozytywny trend kładący nacisk na wykorzystanie istniejących budynków. *Adaptive re-use* pozwala na wprowadzenie nowej funkcji obiektu przy zachowaniu jego oryginalnej struktury. Tego typu działania mogą pomóc w zachowaniu historycznych wartości budynku, mają również zalety edukacyjne, ekologiczne i ekonomiczne. Rodzi się jednak pytanie: czy każdy obiekt można dowolnie zaadaptować? Niniejszy artykuł bada kwestię dawnych więzień, które zostały zaadaptowane jako m.in. hotele i muzea. Poznanie historii architektury więziennej i przykładów sposobu zachowania i ponownego wykorzystania tych obiektów może pomóc w odnalezieniu dla nich odpowiedniej nowej funkcji, a zarazem posłużyć jako przykład dla innych, obecnie opuszczanych budynków więziennych.

Słowa kluczowe: architektura, więzienia, adaptacje, architektura penitencjarna, dziedzictwo, panoptikon

1. Introduction

In recent years, the potential of abandoned buildings which we have inherited from the past has been noted. These objects could serve as catalysts in revitalising devastated urban areas. What is more, adaptive re-use has also many other advantages which are connected with economic and ecological studies [11]. Although, attention was focussed on designing new buildings for many years [12], today there is a growing trend for adapting existing, abandoned structures rather than constructing new objects. Such a solution is continuously gaining in popularity and this is evident in projects of students of architecture as well as in studies conducted by experienced architects and researchers [20]. Former factory sites, old shipyards and sacred buildings have, in recent years, become the subjects of many studies [16, 6, 3, 22]. These properties do not give rise to negative emotions and they have therefore been adapted for various functions. In contrast to the above, this article focuses on abandoned structures and it examines the possibilities of the adaptation of buildings which are named in literature as 'dark heritage', 'difficult heritage', 'dissonant heritage', 'heritage that hurts' etc. [19]. These places are associated with tragedies, death, crime, violence. All of them could cause negative emotions as well as a sense of fear. This group of objects includes concentration camps and prisons. Such places remind us of torture and despair; however, they are still simply buildings which require some action aimed at saving them before they fall into disrepair. This article aims to answer the question of whether it is possible to 'erase' and break the negative emotions related to the prisons and use them again as public buildings.

The preparatory phase of the study was to become familiar with a group of objects that are marked as dark heritage. From this group, European correctional facilities that had stopped to fulfil their primary function before the first half of the twentieth century were selected. The next step of the study was to examine the fate of the selected objects after changing their original function. The background for the research was to study the history of the development of prison architecture. Such a scheme of activities allowed distinguishing two groups among the adapted correctional facilities. The development of the prison system and its architectural transformation is based on source materials [1, 2, 5, 7, 9, 13, 15, 18, 28–31] as well as in situ observation. In this research, a comparative method and a logical argumentation were used. Owing to the presented activities, it became possible to divide the adapted prisons into two groups and present the possibilities of their reuse. The benefits of these solutions has been shown. All of this could serve as examples for other prisons that remain abandoned.

2. Historical background

The first prisons could be found in ancient times in Babylon, Egypt, Greece and Rome. There is not much information about them due to the fact that it is difficult to determine the structure of these buildings. Many of them were destroyed or covered by the subsequent layers of later constructions. In ancient Greece, men could be imprisoned for high treason or offense against the government. Life imprisonment was not a sort of a penalty then. A prison

was a place for detention prior to trial or it was used to force debtors to pay their debts. Roman law recognised only a death sentence or fines. Later, corporal punishment and forced labour were added. In Greece and Rome there were private prisons (*carcer privatus*) which were used only to coercion someone who did not want to pay. There were also public prisons which were used before trial or execution [7].

The Mamertine Prison, a Roman private prison which is located near the Forum Romanum, is an example of an ancient prison about which something is known. It was probably constructed around 300–200 B.C. Excavations which were performed in 1870 contributed to many interpretations of how the prison could have looked like. The remaining parts from the structure show that there were two chambers: a lower and an upper chamber. Only the upper chamber has some light which was provided only through an oculus or a hole made in the ceiling. This one might have been used for the confinement of minor criminals whereas the dark, lower pit may have been used instead of the death penalty [7, 1].

The growing popularity of the prisons could be associated with the position of the Church, which negatively referred to the death penalty and corporal punishment. In the thirteenth century, the Pope permitted imprisonment as a penalty for members of the public. However, treatment of the prisoners did not change much in the light of antiquity – they were still deprived of dignity and the penalty was characterised by brutality. It was common to subject the prisoners to torture until they confessed their guilt. Imprisonment resulted in slow death from starvation, inadequate clothing and lack of air. The prisons were often located in dungeons where there was no access to natural light and moisture dominated. Others could be found in the gatehouse, castles, fortresses etc. There were also manorial prisons which aimed to hold serfs captive. Many city gates were used as a prison, for instance Royal Prison, the Bastille in Paris.

Government funds did not usually allow construction of a new building for the prison function and because of this, criminals were incarcerated in already existing structures as shown above. Constructing objects especially for this purpose came later [1, 7, 2]. In the middle ages, many cities probably had their own small prison. These objects were usually small, wooden and with one room. The largest one could probably accommodate up to thirty prisoners. Not much is known about the architecture of these facilities. Their arrangement was makeshift which was probably associated with the uncertain financing of construction and maintenance. Nevertheless, a division of criminals also appeared there – most dangerous prisoners were incarcerated in underground chambers. Before the end of the thirteenth century, it was possible to recognise separate rooms for women [7].

Around the seventeenth century, prisons were constructed on a larger scale in Europe. This was connected with a recognition of the human dignity of the prisoners which led to the development of prison architecture in all countries. At the end of the eighteenth century, the panopticon model (Fig. 1) was designed by Jeremy Bentham. The draft presented the design of a prison in a shape of a circle with a head keeper's house located in the centre and surrounded by cells arranged in tiers. Such a solution allowed observation of the prisoners from the central tower but they did not know if and when they were observed because of reflecting light in the windows of the tower. The continual sense of surveillance aimed to

motivate prisoners to control their behaviour. This model reflected an idea that controlling inmates' minds might become a substitute or corporal penalties. Although this project was not implemented, other architects drew from this idea what is visible, for instance, in the project of the HM Prison Pentonville (Fig. 2).

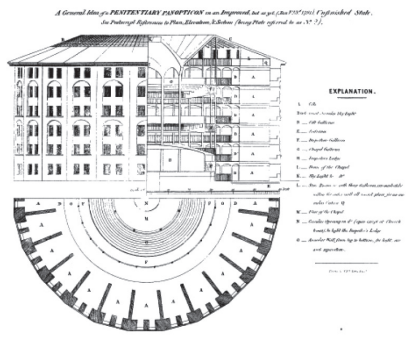

Fig. 1. The panopticon prison design by Jeremy Bentham [36]

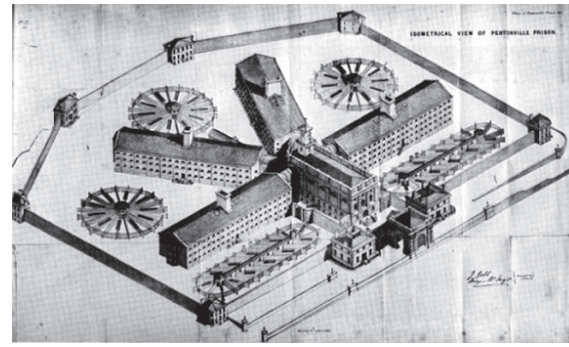

Fig. 2. Isometric drawing of the HM Prison Pentonville [37]

Contemporary architecture of prisons is guided by completely different rules which follow the changing philosophical trend and an understanding of the main aim of the punishment – to reform the prisoners. This goal could be achieved by adequate architecture, which is the current subject of research [12, 13].

3. Different ways of adapting penitentiary facilities

This section presents European examples of prisons which stopped their original functions by the end of the first half of twentieth century. Each one of the examined facilities was adapted to a new function.

3.1. The Warszawa-Mokotów custodial facility, Poland

A custodial facility was opened in Warsaw by the Russian authorities in 1904. It was arranged for 800 prisoners, there was a kitchen, ironworks, hospital, bakery, carpentry shop etc. It also had a power station. All of these made it one of the most modern facilities of this type in Russia. In this building, mainly political prisoners were incarcerated. In 1915, Germany captured Warsaw and changed the name of the facility to 'Criminal Prison in Mokotów'. In the nineteen-thirties, the prison was attributed to a group of prisons which were intended for heavy penalty incarceration. Under German rule, this facility was the most overcrowded – at the same time, about 2500 people were imprisoned. From Warsaw, prisoners were exported to other prisons or concentration camps. The prison in Warsaw was used also for mass executions. After the war, the prison served as the Central Prison for Political Prisoners in Poland. After the fall of communism, the building was rebuilt and renovated.

In 1993, within the framework of rehabilitation activities and the fight against addictions, a department for the treatment of alcoholism was established in the former prison. After ten years, a modern pavilion was put into service. It was designed for prisoners who were dangerous to the public and other inmates. In 2011, a memorial place devoted to the history of the prison was opened in the area of the former penitentiary facility [28]. In 2016, the Minister of Justice announced the liquidation of the prison and intended its area for a museum. The exhibition in the Museum of Cursed Soldiers & Political Prisoners aimed to awaken people's reflection on Polish patriotism and show the history of people who in the name of higher values spent their lives in the fight against the form of government [29].

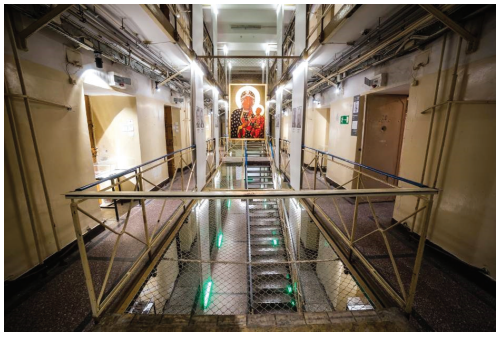

Fig. 3. Former prison in Warsaw – a corridor [24]

Fig. 4. Former prison in Warsaw – a former cell which belongs to the museum exposition [24]

3.2. Prison in Kielce, Poland

The prison in Kielce was constructed at the beginning of the nineteenth century. When it was taken under Russian rule, it was enlarged and it has existed in this form up to the present day. It was later taken under German management. At that time, there were about

Fig. 5. Former prison in Kielce, a main gate [27]

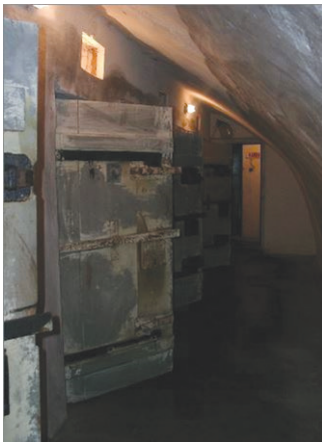

Fig. 6. Former prison in Kielce, interior [27]

2000 prisoners while its capacity was dedicated for 400. Prisoners were starved, killed, taken for execution, to concentration camps or forced labour. After the war, it served as a place of incarceration under the rules of the Polish authority until the nineteen-seventies. Due to the transfer of prisoners to a new location, this building became abandoned. In 1995 in the former prison in Kielce, a memorial place was arranged and the Museum of National Remembrance was opened. Between 2010 and 2012, refurbishment of the object was conducted and a new conference room and exhibition halls were planned. In the halls there are exhibits related to the history and fate of the prisoners, for instance, an original hook which was used for the implementation of the death sentence by hanging [5, 25, 26, 30].

3.3. Prison in Hasselt, Belgium

This prison was built in 1859 in Hasselt; it fulfilled its function up until 2005. Its plan was inspired by the model of panopticon (Fig. 1). At the end of the nineteenth century, it was seen as not functional. The Limburg University Centre needed more space and as a result, the authorities of the university began to look for a new location for the Centre of the Faculty of Law, the dean's office and other facilities. In actuality, the building of the former prison satisfied the needs of the university even though it totally differed from what the authorities had envisaged as a future location. A project for the adaptation of this facility was chosen through a competition. The selected project incorporated the dean's office, a café, meeting places and student spaces in the prison. The Faculty of Law and the rector's office were arranged in new buildings which were added to the prison.

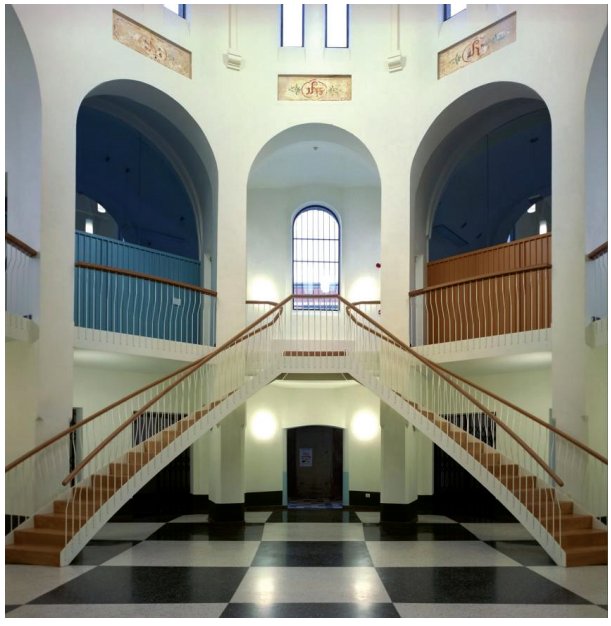

Fig. 7. Former in Prison in Hasselt, interior [31]

Fig. 8. Former in Prison in Hasselt, interior (photo by J. Szczepański)

All of the prison's walls were preserved. The only change which was introduced in the external façade was new doors. The old doors were replaced by fencing doors which enabled a view of the green courtyards behind them. The basic structure of the interior was also preserved. The centre of the panopticon serves as a hall (Fig. 7). A staircase and the floor were replaced. Cells were also preserved and now they function as individual rooms for students (Fig. 8). One of the characteristics of the prisons is the limited access of light. This problem was solved by adding some windows on the roof. The space between the buildings which dates from the nineteenth century and between those which have been recently added is used by the students and also serves as a meeting place or as a huge auditorium for various events (Figs. 9, 10) [18, 15, 31].

Fig. 9. Former in Prison in Hasselt, exterior (photo by J. Szczepański)

Fig. 10. Former in Prison in Hasselt, a bird's-eye view [15]

3.4. The Het Arresthuis Prison, the Netherlands

The Het Arresthuis prison was established in the mid-nineteenth century in the Netherlands. The most dangerous inmates were imprisoned in this object. The prison was closed in 2007. It stopped to fulfil its function after almost 150 years and soon after that, in 2013, it was opened as a hotel.

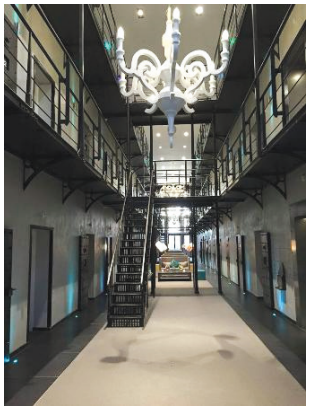

Fig. 11. Former Het Arresthuis Prison, an adapted corridor [33]

Fig.12. Former Het Arresthuis Prison, an adapted cell [33]

The structure and architecture of the former prison was only slightly changed. Over 100 cells were adapted for forty guest rooms which overlook the prison's old corridor (Fig. 11). Some original elements from the nineteenth century were left in the interiors, for example, doors in order to remind about the history of the place. The original elements were combined with modern furniture (Fig. 12). A canteen was located above the rooms, where it is possible to watch a slideshow of a chronicle of the prison during a meal at a common table [14, 32].

3.5. Långholmen Central Prison, Sweden

On the island of Långholmen, which was first mentioned in the fifteenth century, the Långholmen prison was located. In the seventeenth century, a customs house was established there. A few years later, a brewer bought apart of the island and constructed a residence called Alstavik. Soon afterwards, this building was acquired by the state and converted into a prison for women. In later years, it was extended and dominated the island for more than 200 years. In 1975, the prison was closed. Since then, the buildings of the prison slowly fell into disrepair. As a consequence of this, some of the buildings had to be demolished.

Fig. 13. Långholmen Central Prison, 1985 [34]

Fig. 14. Långholmen Central Prison after adaptation [34]

In 1989, a new era in the history of the island began – a youth hotel was opened in the former prison. The cells were converted into hotel rooms (Fig. 15) and a conference room was also incorporated. At present, this place is the combination of a hostel, hotel, museum and conference centre. The hostel is located in the old part of the ground floor. One of the cells is furnished according to the function which it held in the old days. The original windows were preserved as well as the training squares which serves as a café during the summer. One of the attractions is the opportunity to take part in a game which involves playing the role of a prisoner and making an attempt to escape from this facility. The new function of the former prison was selected precisely in order to attract customers through the entire year [34, 35, 17].

Fig. 15. Rooms in the former Långholmen Central Prison [34]

4. Applications and summary

We inherit a lot from the past, not only buildings which prove the genius of human beings but also those that remind us about traumatic events, cruelty or violence. These dark objects evoke strong emotions; however, it should be kept in mind that they are still buildings which underwent a process of decay and deterioration and should be taken care of as every structure. Buildings associated with trauma and violence are called 'difficult heritage', 'dark heritage' and similar, and this group includes concentration camps and prisons. The feeling of empathy for the victims of the cruelty and crimes which were committed in the concentration camps is so strong that it is impossible to adapt them for any other function than a memorial place [19]. Prisons are apparently similar to the above-mentioned objects. From ancient times, prisons were also inhumane places, incarceration usually led to mental exhaustion and harsh

conditions repeatedly led to loss of health and the death of some prisoners [2, 7, 1]. However, the solution to an issue of adaptation of the penitentiary facilities is not obvious.

All of the prisons presented in the article can be linked with stories of crime and violence. Despite this, the analysed examples enable the differentiation of the abandoned prisons into two groups: the first concerns places of death of mostly innocent people, and the second includes those prisons in which serious offenders were incarcerated. The prisons in Warsaw and Kielce which were places of torture and execution of innocent people belong to the first group. Currently, both of these fulfil memorial and museum functions. The buildings from the second group are also associated with violence, but in a completely different dimension to the first group. The inmates incarcerated there had committed crimes. These buildings are not symbols of important events in history, thus they were adapted to community facilities: today the former prison in Hasselt is the headquarters of the University and the former Het Arresthuis Prison and the Långholmen Central Prison are now hotels.

The adaptation of buildings for which the previous function is no longer desired or needed could bring a lot of benefits in various fields. In the first group mentioned above, an inextricable link is visible between the building and the exhibits presented inside. As a result of this, a new function becomes a symbolic continuation of the old function. This kind of adaptive action highlights the authenticity of the exposition and the place even more. It is also indicated that places associated with death are visited because of a desire for educational and emotional experiences. These are also the motives of heritage tourism [4]. Research also shows that a country's heritage is good for tourism, which in turn benefits its economy [21].

The old, untypical structures adapted to new functions, for instance, as hotels, are becoming extremely common due to tourists who are increasingly looking for non standard accommodation. Furthermore, the former prisons also allow guests to take part in unusual activities and games, such as an attempt to escape like a prisoner. There are even weddings hosted in such places. The interest in these objects is also enhanced by the original features which were preserved in them. This provides individuality and originality for adapted place – such as example is a steel door in the hotel in Långholmen [7, 10].

The subjects of this research were prisons which were reused after fulfilling their primary functions. As has been shown, these places are classified in literature as 'difficult heritage'. However, they should not be unequivocally classified. Although prisons are places connected with violence and may cause negative emotions, it is possible to break the prejudices which arose from their original function and find them new, not obvious functions. These buildings can symbolically continue their original function and become memorial places which contribute to the education of young generations. Nevertheless, after a careful diagnosis of the history of the site, it is possible to detach these places from negative emotions and use them as non-memorial places. Adapted prisons could become a catalyst for change and have influence on the development of tourism in their area and thus bring the same economic benefits as any other building. It is important to find a good balance between the commemoration of past events and the introduction of changes to the structures related with history. As a result of this, it is possible to reuse former prisons without causing offence memory of these places. A properly implemented function will contribute to preserving the building and its integration with the contemporary environment.

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The problem of the architectural adaptations of synagogues in north-eastern Poland

Problem adaptacji architektury posynagogalnej na obszarze północno-wschodniej Polski

Abstract

The intention of the subject is to analyse and evaluate examples of the adaptive reuse of synagogal architecture in the area of north-eastern Poland. Several dozen synagogues survived the period of wartime destruction and genocide in these areas, constituting a testimony to the presence of Jewish people there. Both the Holocaust and emigration led to a situation in which these buildings found themselves without owners after the war. During the post-war reconstruction, the problem of their adaptation to new functions arose.

Keywords: architectural adaptation, synagogue

Streszczenie

Podstawowym zamierzeniem artykułu było poddanie analizie i ocenie przykładów adaptacji pożydowskiej architektury sakralnej na obszarze północno-wschodniej Polski. Czas zniszczeń i zagłady wojennej na tych terenach przetrwało w różnym stanie kilkadziesiąt budynków synagog będących świadectwem obecności Żydów na tych terenach. Holocaust i emigracja sprawiły, że po wojnie zabrakło właścicieli tych obiektów, a w czasach odbudowy powojennej pojawił się problem ich przystosowania do nowego przeznaczenia. Przekrój nowych funkcji w adaptowanych obiektach jest zaskakująco szeroki.

Słowa kluczowe: adaptacja architektury, synagoga

1. Introduction

The primary intention of taking up this subject was to perform an analysis and evaluation of examples of the adaptive reuse of formerly Jewish religious architecture in the area of north-eastern Poland. Several dozen buildings have survived the period of wartime destruction and genocide in these areas in various conditions, constituting a testament to the presence of Jewish people in this area. The Holocaust and emigration led to a situation in which these buildings found themselves without their rightful owners and users, and leaving a problem of adapting them to new functions appearing as part of the post-war reconstruction. The scale and essence of the problem has been properly illustrated by Wojciech Wilczyk's artistic project entitled *Niewinne oko nie istnieje*, which presents the post-war fate of synagogues across the whole of Poland [7]. Some of the structures that had been destroyed were rebuilt and adapted to new functions. Other structures, that the war had left in good condition, were paradoxically demolished.

A change in the situation of the heritage of Jewish religious architecture was brought by the Act of 1997 on the Relationship between the State and Jewish Religious Communities. It is on the basis of this act that the Polish Jewish community began to reclaim former synagogues and prayer houses. This justifies the necessity of engaging in studies and developing appropriate methods of revitalising and adapting this category of architecture to functions that honour their former status and that preserve the distinct cultural values that are important not only to the Jewish community, but also, and perhaps most importantly, to Poland.

After performing initial research, a group of twenty three synagogues and prayer houses that survived the war in the area of north-eastern Poland and methods of their adaptive reuse were analysed.

After analysing the collected materials, a division of the buildings and designs of their adaptation was performed in terms of function, which is also associated with the scale of the alteration of their architectural structure.

Four primary groups were distinguished:

- buildings adapted to functions associated with culture (community centres, cinemas, museums, libraries);
- synagogues adapted to sports-related functions (sports halls, gymnastic halls, etc.);
- buildings adapted for use as offices, residential buildings, hotels, commercial spaces, schools;
- outbuildings, storage buildings.

2. Adaptations to functions associated with culture – Synagogues in Tykocin and Siemiatycze

Post-war adaptations to functions associated with culture were planned and executed in numerous synagogues all across the country. As Kazimierz Urban pointed out at the start of the nineteen-fifties, such 'social and cultural purposes' or 'cultural and educational' uses

predominated in the conversion of former synagogue buildings. Functions associated with the promotion of culture, and, by association, tradition and history, aided the preservation and recreation of the architectural decoration of the synagogues that underwent adaptation. The adaptation to a museum building is the option that interferes the least with the structure of former synagogues. Such an adaptation makes it possible to preserve the integrity of the prayer hall and preserve the aron hakodesh, as well as the centrally-located bima. The best examples of this type of adaptation are synagogues in Włodawa and Łęczna, and in Podlachia (Podlasie Region) – the Great Synagogue in Tykocin (Fig. 1). In these buildings, the original interior structure was preserved with the maintenance of the former form of the main prayer hall being a priority (Fig. 2).

Fig. 1. The Great Synagogue in Tykocin, 2013 (photo by Piotr Trojniel)

Fig. 2. The Great Synagogue in Tykocin – interior, 2013 (photo by Piotr Trojniel)

Fig. 3. The Great Synagogue in Siemiatycze, 1925 (photo by Jankiel Tykocki)

Fig. 4. The Great Synagogue in Siemiatycze, 2019 (photo by Piotr Trojniel)

Fig. 5. The Great Synagogue in Siemiatycze – interior, 2019 (photo by Piotr Trojniel)

One of the examples of the aforementioned adaptation method in the area of north-eastern Poland is the Great Synagogue in Siemiatycze (Fig. 3, 4) – an original building that is important because of the use of an elongated spatial layout which would go on to become the typical solution found in nineteenth-century synagogues. The basilica-type layout of the prayer hall is particularly noteworthy; it is probably the first instance of its use in a synagogue in Podlachia and one of the first in Poland. The building played the role of a storage building during the occupation and survived the war as a result; however, its interior and furnishings were destroyed. During a renovation project performed in the nineteen-sixties, the synagogue was converted into a community centre with a cinema hall. Due to the adaptation assuming the function of the main prayer hall as an audience area, the bima was removed. The historical spatial structure of the building interior was preserved. Arched arcade openings in the gallery-mezzanine in the prayer hall were, however, sealed with walls, while partitioned-off spaces were adapted for the purposes of the community centre's exhibition halls (Fig. 5).

3. Adaptation to sports-related functions – the Samuel Mohilewer synagogue in Białystok

The Samuel Mohilewer synagogue, also called *Beit Szmuel*, was one of the most interesting synagogues of Białystok. The architectural design of the synagogue was submitted to the Construction Department in Grodno in 1897; however, its exposed site and proximity to the palace of the Branicki family led to an extension of the construction permit issuance procedure. The Beit Szmuel synagogue was a temple of progressive Jews, which is probably the reason behind the Gothic revival style of its architectural detail, which is rarely encountered in synagogal architecture in Podlachia, and which was further combined with the Baroque composition of the frontal facade [1, p. 53–55]. The design of the richly-decorated two-storey facade was performed in such a way as to feature certain simplifications relative to the design (Fig. 6). The synagogue is also an example of an adaptation to a sports-related function. Adaptive reuse in the form of a sports-related function was facilitated by the traditional functional and spatial layout of the synagogue, with its large main prayer hall space. In the case of these types of solutions, the main hall was typically remodelled into a gymnastics hall or some other form of space used for practicing sports, while the remaining spaces were converted to auxiliary functions (locker rooms, bathrooms, etc. – Fig. 7, 8). This is similar to the case of the synagogue in Suchowola, which was also adapted into a sports hall and the only elements that allow one to glean the previous function is the axial composition of the back facade with tall, arched windows and an external addition that housed the aron hakodesh niche. Only renovation work that was technically essential was performed, with the facade details being removed and the building extended and remodelled during the adaptation to the new function.

Analyses have shown that traces of the original function are erased and destroyed in synagogues that are adapted to sports-related functions. The bima is removed, similar to the location of the aron hakodesh. The traces of the former function are completely erased, which is why adaptations of this type should be viewed negatively.

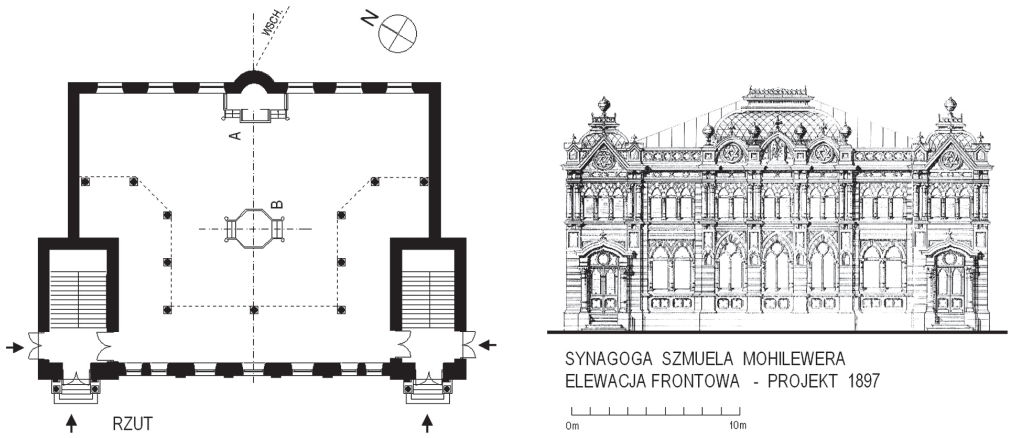

Fig. 6. The Samuel Mohilewer synagogue – architectural design, 1897

Fig. 7. The Samuel Mohilewer synagogue – adaptation and extension, 2013 (photo by Piotr Trojniel)

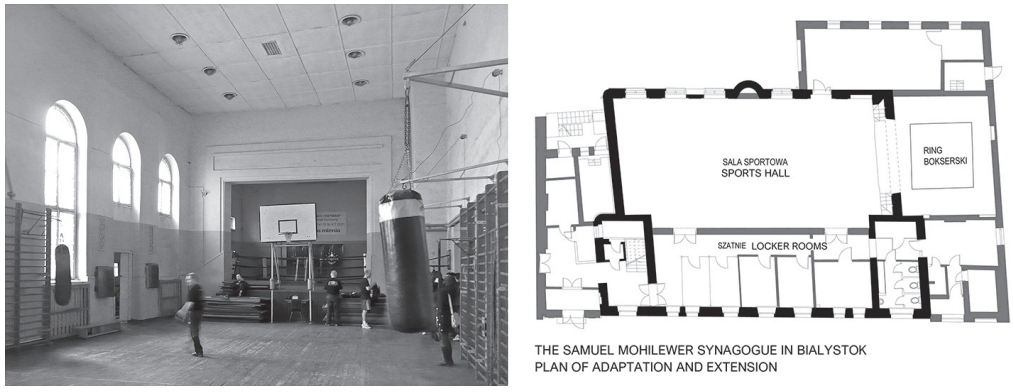

Fig. 8. The Samuel Mohilewer synagogue – photo of former Main Prayer Hall, 2013
Plan of adaptation and extension (drawing by Piotr Trojniel)

4. Adaptations of synagogues for use as offices, residential buildings and hotels – the Talmudic House in Kolno

The surviving building of the former synagogue in Kolno (Fig. 9) was rebuilt after wartime destruction, erasing the traces of the former function and adapting it to a storage building [6, p. 139]. After 1958, it was adapted to a country department store and functioned in this form up until the end of the nineteen-eighties. In later years, the building was not in use; this was probably associated with the unclear legal situation of the former synagogue. It was only in 2008 that the building was taken over by the Jewish Religious Community in Warsaw and its adaptation to a function associated with providing services to tourists was planned. The building was sold, however, and the new owner adapted it to a restaurant with a hotel section. The design was prepared in 2009 by the Expans design office from Łomża [8] and assumed the preservation of the state of the external massing that was the result of post-war remodelling and subsequent adaptation projects. The post-war single-storey extension located in the north-western corner was preserved and converted into a kitchen for the coffee shop and the main restaurant space. The architectural design did not use the opportunity to recreate the tall arched windows in the side facades of the former prayer hall. The small rectangular windows that had existed prior to the adaptation were preserved, although earlier conceptual design proposals assumed the recreation of these windows in an earlier form. The gables of the frontal and eastern facades were also designed to feature additional rectangular windows, which is associated with the function of the hotel placed in the attic spaces of the existing building. As part of the adaptation, the vestibule on the ground floor was designed to house an entrance hall with the hotel's reception

Fig. 9. The Synagogue in Kolno, 2016 (photo by Piotr Trojniel)

area, toilets, a dressing room, and a small coffee shop with a buffet. An open space intended to serve as a multi-functional hall was designed above the ground floor of this section of the building. Inside the former prayer hall, a large restaurant hall that could be converted to be a conference or wedding reception space was designed. Along the northern and southern side walls, mezzanines were designed with an open stairwell supported by a steel structure, which raises doubts and disrupts the proportions of the former prayer hall (Fig. 10). This is probably an expression of the desire to secure additional usable floor area in this space. The organising of wedding receptions here is also questionable.

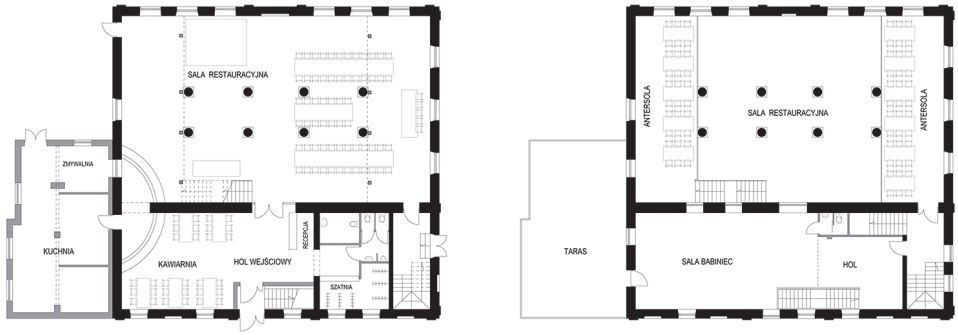

Fig. 10. Plans of the Synagogue in Kolno – design of extension and adaptation, 2009

Analyses of other buildings have shown that adaptations to office, residential and hotel functions are characterised by large-scale alterations in the external form of the building, erasing the traces of their original function, examples of which include former synagogues in Augustów, Białowieża, Rutki-Kossaki and Mielnik. In addition, the remodelling of the interiors and secondary divisions using partition walls and floor slabs cause the past functional layout to be less apparent. Adaptations of this type have been assessed negatively.

5. Adaptation for use as outhouses and storage buildings – the Jentes Bet Midrasz synagogue in Krynki and the synagogue in Czyżewo Osada

The Jentes Bet Midrasz synagogue in Krynki was built in the second half of the nineteenth century; it was founded by Jenta Rafałowska-Wolfson, hence its name. The hypothesis concerning the building's construction at the end of the nineteenth century is supported by the eclectic architecture of the building in the so-called brick style, which was distinct for Podlachia towards the end of the nineteenth century (Fig. 12). The building was built on a floor plan with a shape similar to that of a square, in the frontage of what is now Czysta Street (formerly Łazienna Street), with its eastern facade facing towards the street. The synagogue was orientated, as demonstrated by the niche in its eastern facade and a pair of lesenes signifying the placement of the aron hakodesh. The building survived the war and was adapted to an outbuilding storage space and has served its successive owners in this form to this day.

Fig. 11. The Synagogue in Kolno, 2016 (photo by Piotr Trojniel)

Fig. 12. The Jentes Bet Midrasz synagogue in Krynki, 2013 (photo by Piotr Trojniel)

Another interesting building is the synagogue in Czyżewo. After the war, around 1950, its damaged north-western corner was rebuilt and the building was adapted to serve as a storehouse; it has been used in this capacity to the present day (Fig. 11). Designs of the synagogue's adaptation to a municipality office building that were prepared in 1982 have remained unused. In 1995, as a part of a renovation project and adaptation to the function of a shop and storage space, the windows were replaced and the layout of the southern facade was corrected, restoring its quintaxial layout.

The adaptive reuse of synagogues as outbuildings, seemingly random in functional terms, facilitate the decay of the buildings and the erasure of their past as religious structures. These adaptations are limited solely to the necessary remodelling and renovation, thanks to which, these buildings, despite ongoing technical degradation, paradoxically remain similar to their original form, enabling reconstruction combined with adaptive reuse.

6. Demolished buildings

Buildings that had survived the war but were later demolished constitute a separate and essential group. These were the synagogues in Ciechanowiec (New Bet Midrash), Knyszyn (Bet Jeszurun), Krynki (the Great Synagogue) (Fig. 13), Sokółka (the Great Synagogue) and Suwałki (the Great Synagogue) (Fig. 14). Despite planned adaptive reuse for cultural purposes, and despite their good technical conditions (excluding the Great Synagogue in Krynki), these synagogues were demolished. It appears that, particularly in the case of the representative structures of the Great Synagogues in Krynki, Sokółka and Suwałki, this constituted a loss to the architecture of the region.

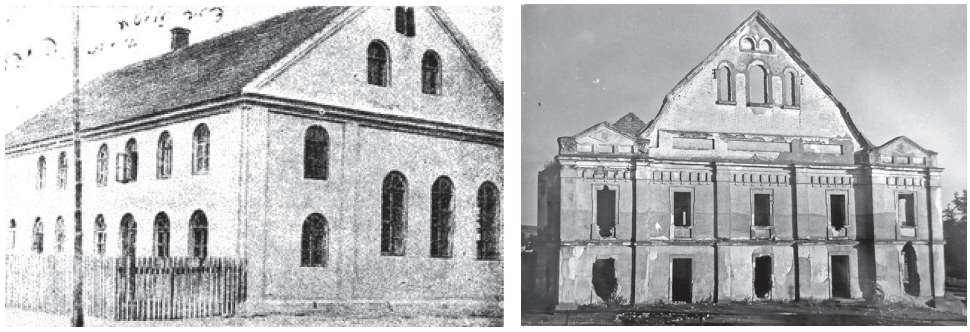

Fig. 13. The New Bet Midrash in Ciechanowiec, 1958 (source: Ciechanowiec Yizkor Book)
The Great Synagogue in Krynki (photo by J. Kazimierski , J. Szandomirski)

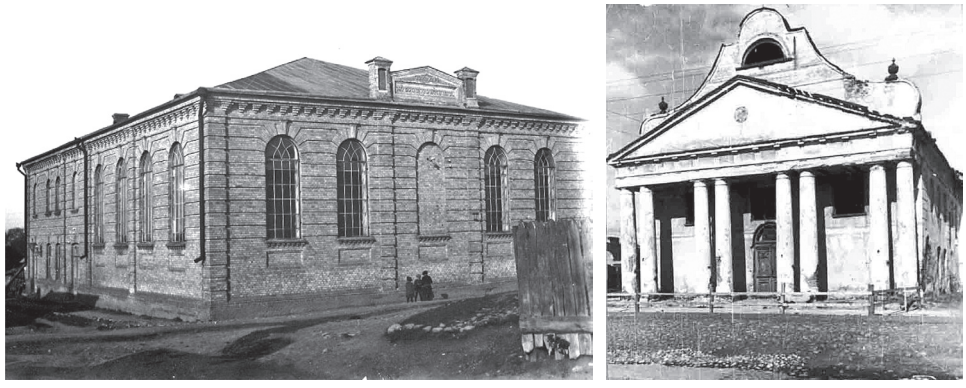

Fig. 14. The Great Synagogue in Sokółka, 1955 (source: Archive of the Sokólka Land Museum)
The Great Synagogue in Suwałki (photo by W. Paszkowski)

7. Conclusions

The array of new functions observed in the adapted buildings is surprisingly wide. From museums, numerous community centres, cinemas, libraries, shops, restaurants, residential functions, to storehouses and outbuildings. In the case of many of these, the question of whether we are dealing with the profanation of the religious spaces of the former synagogues begs to be asked. Ewa Kuryłowicz, in the context of the adaptation of former religious buildings of various faiths, introduced the term 'dignity in the identity of architecture', defining the limits of alterations in adaptation projects of this type of architecture as delineating 'a stage in which the dignity of their spaces is not being stripped away' [3]. In this context, it appears that many synagogues – not only those confined to the area of north-eastern Poland – have been stripped of their dignity. Post-war adaptations in numerous cases have, either deliberately or unintentionally, destroyed the elements that were proof of their past functions, but, as Adam Mazur pointed out, however, that synagogues adapted to new, surprising purposes are not only 'used', but are also brought to life [7, p. 11].

The author's studies have shown that the functions that can result in the least amount of interference with the adapted functional and spatial structure of a synagogue are those associated with culture. The function that interferes with the layout of a synagogue the least is its adaptation to a museum. This type of adaptive reuse of a synagogue building makes it possible to preserve the integrity of the prayer hall and maintain the aron hakodesh, as well as the traditionally centrally-placed bima, as is the case with the Great Synagogue in Tykocin. Solutions that provide an opportunity for flexibly adapting the spaces, as in the case of a recently completed adaptation – the White Stork Synagogue in Wrocław – which is not only a prayer house, but also a community centre (where lectures and concerts are organised), a museum and where the bima was recreated as a mobile form, placed at its central location for the duration of prayer.

Studies of other examples of historical synagogues in the region have shown that, despite their adaptive reuse to functions associated with culture, as in the case of the Cytron Synagogue in Białystok, their external form and internal structure has either been subjected to significant alteration or was destroyed. These actions were also associated with destroying a synagogue's bima and aron hakodesh. This demonstrates that the adaptive reuse of synagogues as culture-generating functions does not always guarantee the safeguarding of the dignity of their space, and is also often associated with their profanation.

The function associated with culture, which is the most suitable in the case of the adaptive reuse of historical synagogues provided that functioning in their original capacity is no longer possible, must be combined with an informed shaping of their functional programme tailored to the building being adapted. Only this combination of programmatic assumptions associated with recreating forms of historical architecture will allow us to properly respect the surviving solutions of the internal structure of the buildings undergoing adaptation, which in the case of synagogues, should be based on preserving the integrity of the prayer hall spaces. It appears that such assumptions have been implemented in the latest successful adaptations of historical synagogues in Płock, Chmielnik (Fig. 15) and Ostrów Wielkopolski.

Fig. 15. The Synagogue in Chmielnik, Design of adaptation: Nizio Design, 2018 (photo by Piotr Trojniel)

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On the spirit of places of worship – practical ecumenism of the Polish cultural borderland

O duchu miejsc kultu – ekumenizm stosowany polskiego pogranicza kultur

Abstract

This paper presents selected examples of interaction between architecture, iconography and theology in contemporary Orthodox, Greek- and Roman-Catholic religious architecture built after the World War II period in Poland. It also shows the process of the evolution of traditional spatial and functional structures and applications of new iconography conventions in Christian temples. It covers problems in art as well as new essential ideological aspects of a symbological and liturgical nature. Examples of modern churches seem to prove that the separatist tendencies of Christian Churches and cultures are now being reversed; this is not only an outcome of mutual dialogue, exchange of ideas, values and different forms of worship, but it also confirms the authentic will of ecumenical unity in art. These examples are representative of the architecture of the cultural borderland, which attempts to synthesise both Western and Eastern Christian art.

Keywords: architecture, art, icon, theology, dialogue

Streszczenie

W artykule przedstawiono wybrane przykłady interakcji między architekturą, ikonografią chrześcijańską a teologią we współczesnej ortodoksyjnej, greckokatolickiej i rzymskokatolickiej architekturze sakralnej, zbudowanej po II wojnie światowej w Polsce. Ukazano proces ewolucji tradycyjnych konwencji architektonicznych i ikonograficznych. Ujawniono problemy sztuki oraz jej nowe, istotne aspekty ideologiczne natury symbolologicznej i liturgicznej. Przykłady współczesnych świątyń dowodzą odwrócenia separacyjnych tendencji chrześcijańskich Kościołów i kultur, co jest nie tylko symptomem wzajemnego dialogu, wymiany idei, wartości i różnych form kultu, lecz także symptomem potwierdzającym autentyczną wolę ekumenicznej jedności w sztuce. Przykłady te reprezentują architekturę pogranicza kulturowego i są próbą syntezy sztuki chrześcijańskiego Zachodu i Wschodu.

Słowa kluczowe: architektura, sztuka, ikona, teologia, dialog

1. The profane versus the sacred

The existence of borderlands between cultures, nations and religions is a highly fascinating phenomenon. It inspires and even provokes reflection, but sometimes it is also highly dangerous as it refers to past conflicts and prejudices. Such was the case all across the world, after all. And it still is. Religious conflicts do take place and architecture, in a sense, is also a part of them. This has been proven throughout history both through acts of the mutual demolition of temples and opposition to their construction, as well as cases of mutual inversions and conversions, mutual remodelling projects and adaptations of Catholic churches, Protestant churches, Orthodox churches, mosques and synagogues. They are visible proof of ever-present religious exclusivism – of religious mission and of opposition towards religion, of proselytism and even religious wars. It is so all around the world and it is so within Christianity itself – from Scandinavia to the Balkans. It has been like this in Lithuania and in Ruthenia, in Hungary and in Romania. It is the same in the Balkans, in Turkey, Syria and Egypt to this day. We too have participated in this process of appropriation and exclusivism in Poland, from the dawn of history up to the present day. We were neither worse nor better.

Today, however, something has drastically changed in the world of the religious man's spiritual values. As before, temples are being demolished by all sides in Africa or in the Middle East, or are being adapted or converted into places of worship of another religion. But they are also being demolished in the West. In a fit of raging secularisation, they are either being demolished or converted to purposes that do not befit their former religious status. The significant escalation in aggression towards the sacred is progressing. From a complete negation of spirituality and total secularisation – to religious proselytising and religious war.

This cannot be ignored today. Forecasts and reported data are frightening. For instance – according to official forecasts of the Observatoire du Patrimoine Religieux – while there are around 100,000 Christian places of worship in France, including 45,000 parish churches, it is estimated that between 5,000–10,000 municipally managed temples will be demolished by the year 2030, which accounts for 5–10% of all temples. This is also happening in Germany, the Netherlands, Great Britain, Ireland, Austria and even in Italy. In countries of Western Europe – just as in countries subjected to totalitarian communist rule until recently, particularly in the USSR, where 70,000 temples were destroyed during the communist period – they are once again being programmatically demolished or converted into restaurants, discos, storage buildings, hotels, shops, car repair shops and garages, and even into public houses and toilets. This was and is also happening here. We do this gladly in Poland as well. We are also guilty of sin.

Perhaps this is not the time and place to discuss this hurtful phenomenon in the context of deliberations on the culture of the Republic of Poland and its heritage – on the one-hundredth anniversary of it being restored to independence. But are historic moments and most important anniversaries not an excellent pretext for a moment of deeper reflection and thought on the various stages of Polish past or discussing difficult subjects? Perhaps it is the other way around, and the situation is better here than elsewhere? Perhaps we have more reasons to be hopeful, to have faith in a better future – one that brings joy and consolation in truth, good and beauty?

2. The borderland

Poland lies in a cultural, religious and national borderland. Both in its past and current state borders it has been situated on a border that divides Europe between Roman and Latin culture and Greek and Slavic culture. Christianity has breathed with two pairs of lungs here for a very long time. Wonderful temples stand here: Catholic, Orthodox and Protestant churches, in addition to molennas. Here, the bodies of ancestors lie together in ecumenical cemeteries. From generation to generation, their memory is celebrated. Eternal memory.

Roman Catholicism and Orthodox Christianity have co-created the Christian spirituality of the Republic of Poland for over a thousand years. They are its autochthonic parts. They jointly shape its national and ethnic awareness. They build its culture and religious identity. Worshippers of the Greek faith – as Orthodox Christians were once known – constituted almost half of its residents, and more than half until the Union of Brześć of 1596. For over three centuries up to the present, the Orthodox Church has been the second-largest Christian Church in Poland in terms of the number of faithful. It constitutes a significant minority.

In the past, mutual contact and attempts at exchanging values between the two Christian rites were limited. Both Churches closed themselves off, sensitive to their dogmatic and doctrinal integrity. They often exacerbated their differences, making them more pronounced. They defended themselves from the influx of values that were alien to them, even at the level of spiritual values and art. However, this flow did indeed exist, despite the will of the Churches. Caused by the preferences of rulers and patrons of the arts, and sometimes in a spontaneous and uncontrolled manner, it created the diversity of this value, its synthesis that was difficult to reasonably explain.

Although the separation of both Churches – the Western and the Eastern – became a permanent caesura in the history of Christianity, for some time now, largely under the influence of ecumenical movements and a reduction of tensions, perhaps due to the numerous temple conversions or as an effect of the Second Vatican Council and joint declarations (for instance the one from Balamand in Lebanon), a certain transmission of values has indeed taken place. We are seeing living symptoms of mutual exchanges in ideas, forms of worship and values – in architecture and the arts – that often stimulate both sides.

Are these symptoms of an ecumenical meeting? Or is it a – jointly postulated by both Churches – 'meeting in truth and love'?

For if not here – this living ecumenism, unburdened by the proselytism and exclusivism of the Churches, without incorporation and combination, without mixing and without division, in direct contact, in such a large and rich alloy of cultures and religions, with such a representation of nations In that, historically, lived as a community and that experienced tragic divisions: both social, local and sometimes familial – then where should it take root?

Particularly here, in the borderland, in the east of Poland, we today often encounter cases of joint ecumenical services. Prayer weeks, joint Bible translations, the joint blessing of places of worship and public buildings, joint state celebrations, weddings and funerals, joint Catholic and Orthodox holidays included in both calendars.

However, the question of whether the time has come to start building joint temples begs to be asked. Is it time for a joint space for prayer to be performed forever – perhaps not in intercommunion yet, but jointly, at one altar, perhaps separately and not at the same time – but nevertheless the same one?

We do have some experience in this, that is quite recent. Perhaps it is not fully the result of the new 'meeting' of the Churches in the spirit of 'truth and love', for this has come about either as a result of conversion or being forced to jointly use the same temples. However, the meeting has taken place sometimes lasting several decades. It is taken part in by both Roman Catholics and Orthodox Christians, Evangelicals and Greek Catholics. At one altar – as it has taken place to this day in Kulno, and – until recently – in the Lemko Orthodox church in Bielanka. And at separate altars – like in the Orthodox church in Zdynia, or the Evangelical church in Pasłęk – but in a common prayer space. After all, this was seen as almost impossible until only relatively recently.

Admittedly, this phenomenon of the exchange of values is not entirely new; it has existed in this part of the borderland for a very long time. One example is the penetration of musical culture to Red Ruthenia from Poland with her Roman polyphony. Another is the adoption of scholastic theology by Kiev and Moscow in the times of metropolitan bishop Piotr Mohyła in the seventeenth century. Another is the later incorporation of Gothic, Renaissance and Baroque elements in the architecture and art of Orthodox churches.

The emergence of the rather peculiar alliance of the eastern icon with the Western Gothic style is quite a phenomenon in Poland. Examples include the fifteenth-century Ruthenian and Byzantine frescoes in the churches of the period of the first Jagiellons, the Gothic architecture of Lithuanian and Belarusian Orthodox churches, as well as the Ukrainian churches of the fifteenth and sixteenth century.

In the Castle Chapel of the Holy Trinity, founded by King Jagiełło, all the walls, the column and the vaults were densely covered with icons by Ruthenian painters (Fig. 1). In the collegiate church in Wiślica, built by King Casimir the Great, beautiful fragments of iconography from around 1400 have survived. The presbytery of the Sandomierz collegiate church was covered in eastern icon paintings ca. 1423. Soon after, additional paintings were uncovered and subjected to conservation. Finally, in the so-called Jagiellonian Chapel of the Cross and the Holy Spirit of the Wawel Cathedral, founded by King Casimir IV Jagiellon, which is counted among its most valuable interiors, Ruthenian and Byzantine Pskov school frescoes were painted. All of these exceptional paintings harmonise excellently with the Gothic geometry of the vault divisions. Their value primarily lies in synthesis – in the harmonious relationship between Gothic architecture and the art of the icon.

One special case of the alliance of Orthodox religious art with the Gothic style is a group of Byzantine and Gothic Orthodox churches from the fifteenth and sixteenth century. They comprise a typologically separate group of defensive, nine-bay, cruciform or cruciform and dome-covered temples, with either one or three apses, flanked by four towers. What is most attractive in them is their Gothic outer costume, which they seemingly put on. They feature Gothic patterns of groin, diamond and star vaults, gabled roofs, portals and windows with pointed arches, brick patterns, rhomboid decorations or Gothic brick. But the manner of combining all of this into a whole of liturgical and spatial orders – of forms of decoration

or iconography – is completely different and distinctively eastern. This group includes Orthodox churches in Synkowicze, Nowogródek, Mołomożejków, Kodeń, Brześć or Vilnius. The katholikon of the Annunciation in Supraśl (Fig. 2), with its groin and dome interior disposition and Gothic vault, wall and column structure, features exceptionally valuable frescoes made by the artel of the Serbian Monk Nectarius – the monk who is probably also the author of the famous hermeneia.

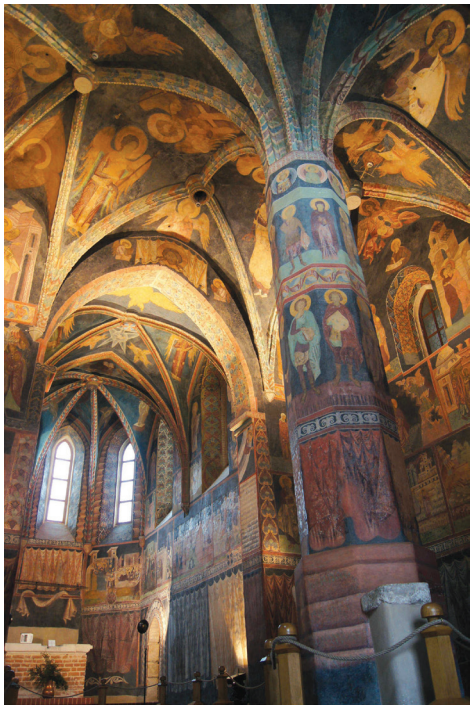

Fig. 1. The Castle Chapel of the Holy Trinity in Lublin (photo by author)

Fig. 2. The Orthodox katholikon of the Annunciation to the Blessed Virgin Mary in Supraśl Lavra (photo by author)

3. The East

The adaptations of post-Evangelical churches of Lower Silesia, Pomerania and Warmia and Masuria to satisfy the religious needs of the Orthodox and Greek Catholic populations that were displaced from their homes after Operation 'Vistula' in 1947 are contemporary examples of this extraordinary alliance.

One of the first examples is the cathedral of the Birth of the Mother of God in Wrocław. This historical Gothic church of St. Barbara, initially Roman Catholic and then Evangelical, is now an Orthodox temple. The authors of the adaptation of its interiors were Jerzy Nowosielski and Adam Stalony-Dobrzański. The ideological programme of the iconography here is built by eschatology. It reveals itself in the iconostasis, with its row of icons depicting – as in the former Gothic altar of the church – the history of the earthly life of Christ (Fig. 3).

The iconostasis is almost an openwork form that is Gothic in its structure. It combines a deep presbytery with the naos of the Orthodox church. The large choros builds the central character of the space. It 'climbs down' from above, as if it wanted to replace the dome that is traditionally placed there, a dome which we never encounter in western Gothic temples but that is necessary in an Orthodox one. The iconostasis is crowned and ideologically connected by the elevated Crucifixion. It connects the theological programme with the paintings of the vaults; it references Italian paintings of the thirteenth century. Returning to times of the separation of both traditions – Greek and Latin – it attempts to bring them closer together [1].

Stained-glass windows are a technique and philosophy of painting with light that has been taken from the West and developed in a manner appropriate to the icon. Typically for Byzantine apses, the eastern one displays the Mother of God – the Sign, with a cycle of scenes from Her life. Also classically, the Western one depicts the Last Judgement.

The Orthodox church of the Dormition of the Mother of God in Krakow is located in a townhouse from the end of the fourteenth century that was later adapted to serve as a synagogue. Its unique iconography was created towards the end of the 1990s by Jerzy Nowosielski. The eastern orthodox temple is depicted on the fresco on the arcade of the vestibule – Praise to the Mother of God. The spatial layout resembles the naves of Evangelical churches with their galleries, and partially the pronaos of Lemko Orthodox churches. The historical two-row iconostasis has been supplemented with new icons in the Sovereign tier. However, it did not feature the necessary scene of the Deesis, which is why it was placed behind the iconostasis on the axis of the wall. Christ Pantocrator with the Little Deesis and the Mother of God and St. John the Baptist. Above them are the Mandylion and the Oranta, while below is the icon of Christ's Descent into the Hell. All of the icons are flanked by abstract and figurative stained-glass windows featuring geometricized symbols of the angelic world (Fig. 4). Thanks to the superimposition of two planes in space, the historical iconostasis, the icons and the stained-glass windows create the joint gabled composition of the new iconostasis. They bind the iconostasis with the 'eastern wall' of the hieratheion. The entirety is crowned by the icon of the Oranta, which has been ever present in the apses of Orthodox churches.

Above the temple, in the refectory, stands the iconostasis that Nowosielski painted for the small village of Orzeszkowo near Hajnówka. There, in opposition to their priest, 'the people of God' did not allow it to be taken inside the church. It was too difficult, too modern, too simple and incomprehensible for them. The beautiful work of the ingenious master clashed with the devotional expectations of the faithful – for neither the first nor the last time in his life. Nowosielski painted the most beautiful icons in the 1990s in this refectory, on the 'living' wall-boarding wood. Naturally, the wood can be seen through them. It marks its existence in the world of temple art. Icons sanctify nature, they lead it further into an unbelievable world (Fig. 5).

When discussing temple conversions and their ecumenical adaptation to a different denomination than the original, largely through iconic efforts, it is also worth mentioning three peculiar Greek Catholic churches.

For the first – the Uniate church in Wrocław – the crypt of St. Bartholomew, which is located in the lower church of the Collegiate of the Holy Cross, Jerzy Nowosielski prepared an

Fig. 3. The Orthodox cathedral of the Birth of the Mother of God in Wrocław. Interior design and iconography by Jerzy Nowosielski (photo by author)

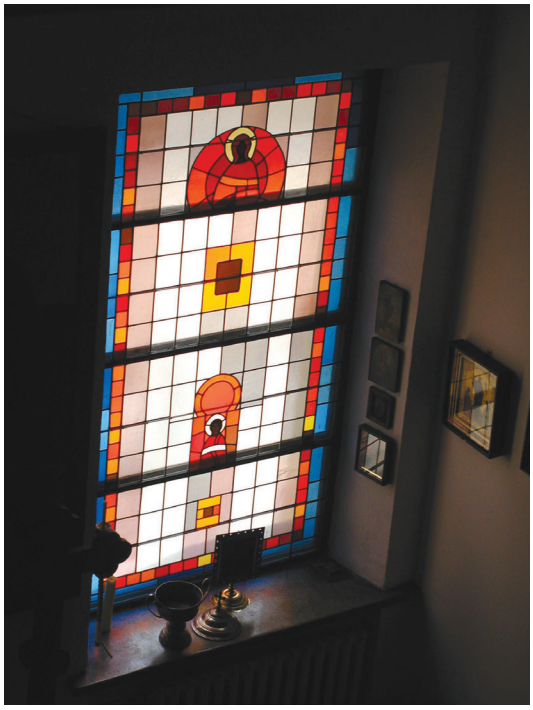

Fig. 4. The Orthodox church of the Dormition of the Mother of God in Krakow. Stained-glass windows in hieratejon of the church by Jerzy Nowosielski (photo by author)

Fig. 5. The Orthodox church of the Dormition of the Mother of God in Krakow. The refectory. Iconostasis and iconography by Jerzy Nowosielski (photo by author)

iconostasis, polychrome fragments and interior furnishings in the years 1984–1985. In 1996, 10 stained-glass windows (Fig. 6) were produced according to his design, in addition to banners, liturgical objects and icons. A most beautiful temple was created. Unfortunately, it was not to be so forever. In 1999 the furnishings, apart from the stained-glass windows, were transferred to the renovated cathedral church of St. Vincent and St. Jacob that was converted into a Uniate church.

Of note is the fact that the stained-glass icon is an extraordinary alliance of the icon and Gothic. This is a very dangerous alliance. The icon has its canonical form, set by the many centuries of the tradition of its existence in the East. The stained-glass window, apart from its polygonal structure of surface divisions and the more abstract, non-anthropological imaging convention, uses a different form of the manifestation of light in nature. In the icon it is about reflection, while here it is about going through matter. In the icon it is the light that emanates from it, while here luminescence results from translucence.

Although both methods of depicting sanctity – both techniques of icon painting and stained-glass window production – were used by both Churches, they came to be accentuated differently throughout history and even different, although similar, theological interpretations. They also became a part of the arsenal of tradition in a different manner, and have also remained there in a different form. At present they have become very close to each other. They have also undoubtedly brought the East and West closer together.

Today the cathedral church of St. Vincent and St. Jacob is one of the oldest temples in Wrocław, founded along with a monastery for the Franciscans, who came here from Prague in around 1240. It was a three-nave hall church and had a single or two-aisle presbytery. Its remodelling and extension projects in the fourteenth and fifteenth century provided the church with a very tall and long main nave. After many Franciscans converted to Protestantism at the start of the sixteenth century, it became abandoned and was taken over by the Norbertines, who devoted the temple to St. Vincent. In 1810, after the secularisation of the order, the church was converted to a parish church. In the closing days of the Second World War it suffered heavy damage: its tower collapsed, as did a part of the wall of the aisle and the vaults along with it. It was rebuilt and served as a military church for some time. In 1997 Pope John Paul II and cardinal Henryk Gulbinowicz transferred the temple to the Uniates.

This was not a project planned by Nowosielski, but it was placed in a space that was so different from its original one that it fully and naturally blended into it. The striking monumentalism of the structure takes everything towards the heavens, towards the Gothic vaults. It does not dominate, but also lifts the rather short iconostasis towards them. Semi--openwork, like in Wrocław's Orthodox cathedral, opens and links the nave with the presbytery. It constitutes a sort of geometric sign within space, in the form of a simple traditional cross-beam with a crucifix. It is perceived in an iconic manner only from a position immediately in front of it. Further away, it disappears in the void of the church. The seven 'abstract' icons of the Sovereign tier, placed on the crowning beam in an applicative manner, delicately underscore their theological expression. Crowned with the scene of the Crucifixion and the figures of the Mother of God and St. John the Theologian (Fig. 7), supported by delicate columns, it appears almost identical to the past architrave of the altar templons from Christianity's first millennium.

Fig. 6. The Greek Catholic church in the crypt of St. Bartholomew located in the lower church of the Collegiate of the Holy Cross in Wrocław. Stained-glass windows by Jerzy Nowosielski (photo by author)

Fig. 7. The Greek Catholic church in the cathedral church of St. Vincent and St. Jacob in Wrocław. Iconostasis by Jerzy Nowosielski (photo by author)

This unbridled might of the Gothic walls – their abstract fragmentation into thousands of bricks – excellently corresponds with the abstract mysticism of the iconostasis and the icons. It is simultaneously present and absent, as if suggesting a different religious reality without any devotion, vanity or kitsch. It is austere and solemn, with theological expression. It is an expression reaching to the essence of the sacred – of this there can be no doubt.

Another highly interesting example of the synthesis of the art of the East and the West is the similarly Gothic Roman Catholic church in Górowo Iławeckie (formerly Landsberg), that was built in the years 1335–1367. During the Reformation it became an Evangelical church and in 1980 it started to fulfil the function of a Greek Catholic church of the Exaltation of the Cross. Another unique Eastern Christianity church was created here by Nowosielski in 1985. He did so in an extraordinarily restrained manner by using an iconostasis with a large crowning cross resembling the historical cross of St. Francis (Fig. 8) and icons painted directly on the red, mortared Gothic brick. Images on 'living brick' are a symbolic transmittance of Divinity through matter and its sanctification. The icon of the Mandylion-Acheiropitos is also an additional conveyor of the historical

Fig. 8. The Greek Catholic church of the Exaltation of the Cross in Górowo Iławeckie Iconostasis and iconography by Jerzy Nowosielski (photo by author)

beginnings of the icon, recorded in the legend of King Abgar. This Greek Catholic church is an excellent meeting of the East and the West.

The former missionary church in the complex of the Metropolitan Theological Seminary in Lublin was built in the years 1719–1736. It was expanded around 1890 to include a Gothic Revival chapel as an extension of the presbytery. Intended for use by Greek Catholic clerics, in the years 1988–1989 the chapel became the church of St. Jehoshaphat. It was given a modern iconostasis–tableau, ascetic in its expression, beautifully painted by Professor Jerzy Nowosielski yet again. Restrained in form, yet suggestive in its content, it blends into the Gothic interior as if it were tailored specifically for it (Fig. 9).

The Greek Catholic chapel of the Foundation of St. Vladimir in Krakow, which, unfortunately, has been closed, also appears extraordinary. It served as a place of worship for a very long time. Due to the termination of a rent contract, despite protests from the entire cultural community, it serves a different Lord now. It is currently a restaurant. After the restoration of the chapel, it literally became a restaurant. It was also a masterwork of art, entirety designed and created by Nowosielski (Fig. 10).

One example of an interesting alliance is the Orthodox church of the Birth of the Mother of God in Gródek. Professor Jerzy Nowosielski and Professor Adam Stalony-Dobrzański were the authors of an excellent polychrome, made here in the 1950s. Noble figurative paintings were masterfully combined with the calligraphy of liturgical texts. Unfortunately, the original, beautiful, short and semi-openwork iconostasis did not survive intact. Only its Royal Doors

Fig. 9. The Greek Catholic chapel in the complex of the Metropolitan Theological Seminary in Lublin. Iconostasis by Jerzy Nowosielski (photo by author)

Fig. 10. The Greek Catholic chapel of the Foundation of St. Vladimir in Krakow. Design of interior and iconography by Jerzy Nowosielski (photo by author)

Fig. 11. The Orthodox church of the Birth of the Mother of God in Gródek. Iconography by Adam Stalony-Dobrzański and Jerzy Nowosielski (photo by author)

have survived, and it was truly one of Nowosielski's exceptional works. The stained-glass windows made by Stalony-Dobrzański were also excellent (Fig. 11).

Incidental as it may appear, the most spectacular example of a project from this period is the Orthodox church of the Holy Trinity in Hajnówka, whose construction took place in the years 1973–1992. It is the only Orthodox church of this size and spectacularity in Poland. It is the only traditional and, at the same time, rare example of the avant-garde. Being a reinterpretation of traditional canons, unbound by the burden of historical revival styles, it goes boldly against contemporary changes in culture, particularly in the – currently minimalist – modernist architecture of the West.

Fig. 12. The Orthodox church of the Holy Trinity in Hajnówka. Conceptual painting of the church by Jerzy Nowosielski (photo by author)

This Orthodox church was designed by Jerzy Nowosielski and Aleksander Grygorowicz. Nowosielski was originally the author of the wonderful iconography of the church, both in its interior and on the outside walls. He was also the author of the ideological conceptual proposal of the architecture and its first drawings. Unfortunately, they were not put to use (Fig. 12).

The temple features references to classical cruciform and dome solutions of the inscribed cruciform type. It combines the historical heritage of Orthodox church architecture with contemporary concrete technologies and the possibilities of its sculptural modelling. The interior of the temple is a cruciform, domed, nine-bay structure, classical for Orthodoxy. It is a negative reflection of the external form. It is esoteric, mystical.

That which could be implemented in architecture and remained from the original proposal is the freeform composition, sculptural profile line and the symbolism of forms and orders. It was not possible to implement Nowosielski's icons, and it is for them that the temple was designed. A pity.

The Orthodox baptistery of St. John the Baptist in Bielsk Podlaski is a universal project in terms of its overarching idea. Its interior has an original and absolutely unconventional sign-

-like liturgical area scheme (Fig. 13). It is built up by the red, profiled altar arch – a sign of the Royal Doors of the iconostasis. It highlights the synthetic unity of the vertical and horizontal orientation of the church, focused by this arch at the Eucharistic centre. This spatial message is developed by the icons of the Archangels that are placed underneath the dome of Old Testament Thrones and the symbol-icon of the Holy Ghost. In the niche of its symbolically 'walled up' eastern doors is the Crucifixion. Only the Saviour can pass through here during His 'arrival from on high', on Parousia. It is a true masterwork of contemporary religious art [2].

Fig. 13. The Orthodox baptistery of St. John the Baptist in Bielsk Podlaski. Interior design, altar arch and iconography by Jerzy Nowosielski (photo by author)

4. The West

The past examples of ecumenism in the arts and in architecture have their contemporary continuation in Roman Catholic temples. They are a testament to the universalism of the icon, its journey beyond the borders of cultures. Today the Christian West is developing its mystagogical function. A transfer of spiritual gifts has taken place, from the Eastern Church to the Western one.

The polychromes in the church of the Exaltation of the Holy Cross in the Jelonki district of Warsaw are painted on mortared brick walls. They are not merely the church's decoration or a beautifying addition – they are a deliberate theological message. With the rather pointed structure of the arches and vault surfaces, the applicative dividing lines and signs-icons have a character that clearly neutralises this sharpness, one that is contemplative (Fig. 14).

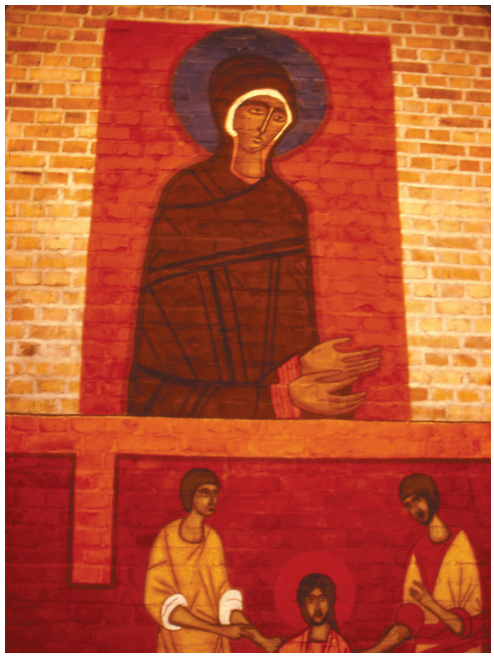

Fig. 14. The Roman Catholic church of the Exaltation of the Holy Cross in the Jelonki district of Warsaw. Iconography by Jerzy Nowosielski (photo by author)

The polychromes of the church in Tychy are wonderful, yet unfinished. The church's intriguing architecture, designed by Stanisław Niemczyk, resembles an archaic desert tent, or perhaps the Old Testament Tabernacle itself. Nowosielski inscribed into it a programme that was compliant with the calling of the church – the Holy Spirit. He is present in the entire structure of the iconography, painted on a tightly boarded cover. This manner of depiction on the visible texture of the base, known from the previously painted Orthodox church of St. Nicholas in Michałowo, became the convention that led the unity of spirit and matter here, melding it into one – a convention of the visibility of matter and its theosis through art (Fig. 15).

This programme is already present in the blue band of the ray that accentuates the main axis of the temple, as if piercing the heavens by the will of the Holy Ghost, symbolically summoned under the guise of a dove. It is present in the little flames that dance in red above the figures of the saints. On the axis, a large figure of a praying Theotokos Oranta is located. She is accompanied by Old Testament patriarchs from the first millennium, prophets and kings, as well as the apostles, martyrs, Fathers and Doctors of a still-undivided Church, of both the East and the West. On the side axis of the transept are two scenes: the Transfiguration and the Crucifixion. At the centre, underneath the skylight of the roof lantern, as if underneath the dome of an Orthodox church, is the scene of the Deesis: the Mother of God, John the Baptist and the veil of the *veraicon* between them. Opposite is the Archangel Michael, who guards the approach.

The Romanesque Revival church of Divine Providence in Wesoła resembles early Christian buildings. It is ascetic, orderly in its structure. The apse is dominated by the Mother of God the Oranta, but without Emanuel in the medallion, as it was initially meant to be. In

Fig. 15. The Roman Catholic church of The Holy Spirit in Tychy. Iconography by Jerzy Nowosielski (photo by author)

Fig. 16. The Roman Catholic church of Divine Providence in Wesoła. Interior design, altar templon and iconography by Jerzy Nowosielski (photo by author)

front of her, on the beam of the templon, is the Crucifixion in a transposition of the Cross of St. Francis. Christ and His Mother are, however, together. This resulted in the spatial superimposition of both depiction planes. The Madonna raises her hands in prayer and the placement of the cross makes it appear as if she is holding it in her open hands. It is a bold innovation, with a deep theological expression (Fig. 16).

On the border between the apse and the nave, Nowosielski built the templon of the altar. An iconostasis was, after all, present in nearly all temples of both Eastern and Western Christians. The architecture is excellently supplemented by an abstract ceiling and stained-glass windows. A true angelology. The cycle of the Stations of the Cross is also a masterpiece. It is drowned in greys, almost without light. Painted with all of the realism of the time and space of historical Jerusalem.

Fig. 17. The Roman Catholic church of the Immaculate Conception in the Azory district of Krakow. Icon of the Mandylion on the retable of the main altar by Jerzy Nowosielski (photo by author)

A similar project is the cycle of the paintings in the church of the Immaculate Conception in the Azory district of Krakow. Here Nowosielski painted the Stations of the Cross and the retable of the main altar. On a large, rectangular panel we can see three of its final stations play out. Painted on pine boards, they display their graining and divisions, their dark knots and the golden tone of the timber. They resemble the truly heavenly gold of the icons (Fig. 17).

Both instances of the Stations of the Cross are a certain breakaway from the classical religious paintings of the West. They are an example of the contemporary, unconventional transposition of the art of the icon. They are proof of the immense possibilities of the development of past canons and the creating of an original icon text that is replete with theological content on their basis.

The Greek Catholic church of the Birth of the Mother of God in Biały Bór was built in the 1990s. It is an innovative work by Nowosielski. It has a universal, super-confessional expression. It is minimalist, as in the West, and iconic, as in the East (Fig. 18). The temple resembles early Christian basilicas with its austerity. The simplicity of forms, the limited lighting and small square and circular windows bring the architecture of Syria, Egypt or Mesopotamia to mind. The external narthex

Fig. 18. The Greek Catholic church of the Birth of the Mother of God in Biały Bór. Architectural design, interior design and iconography by Jerzy Nowosielski (photo by author)

resembles the historical Syrian and Coptic atriums. The interior is central and elongated, with a lowered floor in the centre. The three red arches of the altar partition bring to mind the arch of the baptistery in Bielsko. The meniscus of the quasi-dome builds the vertical axis of the church. It creates the necessary ideological connectivity – although here it does so without the use of light – between the naos with the 'super-heavenly' sphere and the Pantocrator who rules there, unchallenged. Behind the altar, in front of the eastern window of the eastern wall, is a beautifully painted and innovatively placed Crucifixion. It shines with the light of the 'arrival from on high' (Fig. 19).

The two-tower facade opens to all the six cardinal directions. Underneath the towers is the external narthex – resembling the past Syrian and Coptic atriums. At the top there is a double Dutch gable with icons of the archangels Michael and Gabriel, as well as a Greek cross with 5 stigmata. It is this cross that descended to hell. One archangel led it there, and the other triumphantly led it out. It is a beautiful, universal message, written in an old apocryph. Below is the western Veraikon with the transfigured image of the Man of Sorrows.

The cross in the church of St. Dominic in the Służew district of Warszawa is a strong act of religious concentration (Fig. 20). The icon of the Crucifixion became the central icon in its presbytery, ordering and focusing on it its liturgical space. It would be appropriate to note, from Nowosielski, that the depiction of Crucified Christ was the most widespread type of icon in Medieval Italy. Byzantine-Italian crucifixes painted on wooden boards, the *croce dipinta*, are typical of twelfth and thirteenth-century Tuscan art, in addition to the so-called *maniera greca*. They came

Fig. 19. The Greek Catholic church of the Birth of the Mother of God in Biały Bór. The icon of the Crucifixion by Jerzy Nowosielski (photo by author)

Fig. 20. The Roman Catholic church of St. Dominic in the Służew district of Warsaw. The icon of the Crucifixion by Jerzy Nowosielski (photo by author)

to Italy along with Syrian monks. These enormous icons, so-called *croci storiate*, along with the figures of the Mother of God and St. John the Theologian, as well as scenes from the Passion of Christ, once crowned the top of every Italian church's iconostasis architrave. They were commonly called the Cross of St. Francis or the San Damiano Cross. It was this cross that became the subject of St. Francis' contemplation, which was so beautifully depicted by Giotto on his fresco in the church in Assisi. These beautiful icons have survived. They became the connector between the Christian West and East. They remain in this role to this day.

This cross has become an earthly, vertical symbol of Nowosielski's contact with heaven. For true art, a true icon, comes down from heaven. It descends upon us like the holy angels. Such it has always been in the Divine order. Vertically, instead of horizontally.

In the second current of the journey of the art across the borderland, we can mention the contemporary Orthodox church of the Resurrection in Białystok. It has a traditional symbolic structure, being merely clothed in the stylish outer costume of a temple, tailored from Byzantine Gothic. It is, however, a cultural fashion, instead of a worship-related one. It is a structure and 'crystallinity' – the pinnacles, buttresses and gargoyles or cross-shaped applications – that is so distinct of the Gothic style [3].

Fig. 21. The Orthodox church of the Resurrection in Białystok. Architectural design by Jerzy Uścinowicz (photo by author)

The form of the Orthodox church highlights its devotion. The symbolism of the Holy Sepulcher, Anastasis and Jerusalem's Temple of Resurrection is encoded in its geometry. Crystalline forms refer to the Revelation of St. John and his description of New Jerusalem 'coming down out of heaven from God, prepared as a bride beautifully dressed for her husband' (Fig. 21). The interior is completely different: it is circular instead of polygonal, and it is built on the basis of the geometry of the intersection of the shape of the octagon and the Greek cross. The centrally suspended dome, cut off from the vaults using four light arches, is an innovation. They traditionally rise upwards, as in Byzantium, towards its dominance and unreality – towards highlighting its 'super-heavenly' status.

5. Colophon

The art of both Churches – the East and the West – can no longer be separated or pulled apart. They both live in a state of differentiation, but also of a dialectic, potential unity – on the path of 'meeting and dialogue' – particularly here, in Poland, in the borderland. It is worth remembering. It is in these buildings, with all their diversity and similarity, autonomy and unity, that the Christian world returns to its original unity. This unification is taking place naturally,

without being forced. It is being performed in a direct, open way. It took place almost 1,000 years prior to Poland regaining independence in 1918 and has been taking place since. It is not only a meeting. It is not only a dialogue. It is something more. In this attempt at synthesis, art gains meaning and attains its goal. It is fulfilled in what it was, in essence, created for.

Is it not true, then, that – as Fyodor Dostoevsky once said – 'beauty will save the world' [4]? Today we can – although perhaps still timidly – add 'all of it'.

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Model investigations of the aerodynamic coefficients of iced cables in cable-stayed bridges

Badania modelowe współczynników aerodynamicznych oblodzonego cięgna mostu podwieszonego

Abstract

This paper presents the wind tunnel investigations of the mean aerodynamic coefficients of the stationary iced model in cable-stayed bridges. The investigations were performed in a Climatic Wind Tunnel Laboratory at the Czech Academy of Sciences in Telč. The icing of the inclined cable model was made experimentally. The shape of the iced model was mapped by a photogrammetry method. The new iced cable model was made by using a 3D printer. The aerodynamic drag, lift and moment coefficients were determined with respect to three principal angles of wind attack within the range of the Reynolds number between $2.5 \cdot 10^4$ and $13.6 \cdot 10^4$ at a turbulence intensity of 5 %. It was found that the drag coefficient values of the iced cable model are higher than for a circular smooth cylinder. The obtained results could constitute a basis to formulate a mathematical description of the wind load acting on the iced cables of cable-supported bridges.

Keywords: bridge cable, ice accretion, angle of wind attack, aerodynamic coefficient

Streszczenie

W pracy podano sposób i wyniki badań statycznych współczynników aerodynamicznych nieruchomego modelu oblodzonego cięgna mostu podwieszonego. Badania wykonano w tunelu aerodynamicznym Laboratorium Czeskiej Akademii Nauk w Telč. Zrealizowano doświadczalne oblodzenie nachylonego modelu cięgna. Otrzymane oblodzenie zarejestrowano metodą fotogrametrii. Wykonano nowy model oblodzonego cięgna metodą druku 3D. Współczynniki aerodynamiczne wyznaczono przy trzech podstawowych kierunkach napływającego powietrza w zakresie liczby Reynoldsa od $2{,}5 \cdot 10^4$ do $13{,}6 \cdot 10^4$ i przy średniej intensywności turbulencji powietrza 5%. Stwierdzono, że wartości współczynnika oporu aerodynamicznego modelu oblodzonego cięgna są większe w porównaniu do wartości otrzymanych dla cylindra. Otrzymane wyniki mogą stanowić podstawę do sformułowania matematycznego opisu modelu obciążenia wiatrem oblodzonych cięgien mostowych.

Słowa kluczowe: cięgna mostowe, oblodzenie, kąt napływu powietrza, współczynnik aerodynamiczny

1. Introduction

The ice accretion on the slender bridge elements, e.g. the bridge cables, has a significant influence on the flow field around the cables and their aerodynamics and can lead to a much larger amplitude of cable vibrations under wind action than in the case of a dry cable. This statement was confirmed on the basis of the vibration measurements of the iced hanger of the Great Belt Suspension Bridge in Denmark due to the wind, described in the paper [6]. The respective vibration amplitudes of the iced hanger, recorded on March 29, 2001, were approximately 1.4 m in the across-wind direction and approximately 1.0 m in the along-wind direction. It is notable that such large vibration amplitudes were not observed in the case of a dry hanger, i.e. without ice. For this reason, the investigation of the influence of ice on the aerodynamics of the bridge cables is a very important issue when considering the safety of cable-supported bridges.

In the case of an asymmetric airflow around the iced circular cable, an asymmetric distribution of the wind pressure on its surface may occur. For this reason, three aerodynamic coefficients, i.e. drag, lift and moment coefficients should be considered under ice conditions. The values of these coefficients depend on the shape of the ice, wind velocity, turbulence intensity of the airflow, the angle of the wind attack and the character of the flow field in the wake behind the cable. Moreover, an aeroelastic instability of the iced cable known as the galloping instability may occur if the specific criteria proposed by den Hartog [8] are met. This phenomenon is related to the change in the value of the aerodynamic coefficients depending on the angle of the wind attack [4]. The knowledge of the aerodynamic coefficients could be the basis to formulate the mathematical description of the wind load acting on the iced cables of cable-supported bridges in order to predict the cable response due to the wind.

It should be noted that the literature concerning the influence of ice on the aerodynamics of the cables of cable-stayed bridges is relatively poor. Therefore, currently, it is very advisable and valuable to conduct further studies in this field. Some contemporary achievements are presented in the papers [1, 2, 5, 7, 12].

This paper deals with the method and results of wind tunnel investigations of mean aerodynamic coefficients, i.e. drag, lift and moment coefficients of the iced cable model of cable-stayed bridges with respect to three principal angles of wind attack. The tests were performed within the range of the *Reynolds* number (Re) between $2.5 \cdot 10^4$ and $13.6 \cdot 10^4$ at a mean turbulence intensity of 5%. The experiments were carried out in the Climatic Wind Tunnel Laboratory of the Czech Academy of Sciences in Telč.

2. The icing process and the preparation of the iced cable model for aerodynamic investigations

The experimental icing process of a cable section model was conducted in the climatic chamber of the closed-return wind tunnel of CET ITAM [9]. The cable model was made of polyvinylchloride (PVC), whose surface is similar to the surface of a cable cover made of high-density polyethylene (HDPE). The 2.5 m long pipe-shaped model with

a circular cross-section measuring 0.160 m in diameter was inclined at an angle of 30° in the vertical plane, and at an angle of 60° in the horizontal plane with respect to the wind direction. The suspension of the cable model in the climatic section is shown in Fig. 1a. The icing process was performed during a 40 minute time period at an average temperature of slightly below 0°C, a mean free stream velocity of 2.8 m/s with rainy conditions created using rain sprinklers with diameter heads of 2.8 mm. The probability of the ideal meteorological conditions for icing bridge cables occurring naturally is not so high. Roldsgaard et al. [10], estimated that conditions conducive to icing occur for a total of about 96 hours per year, based on monitoring data from the vicinity of the Øresund Bridge in Denmark, using the Bayesian Probabilistic Network.

a) b)

Fig. 1. (a) View of the fixation of the cable model in a special frame in the climatic section during the icing process, and (b) view of the final icing effect from the bottom side of the cable model

The final ice shape on the bottom side of the cable model featured characteristically irregular ice ribs with rounded edges and a relatively maximal surface roughness of 18% (Fig. 1b). On the upper part of the cross-section of the model, the ice was similar to a circular shape with a minimal surface roughness of 0.73%. The relative surface roughness was related to the cable diameter and was measured taking into account only the dominant (most prominent) peaks, which are, in case of the considered model, caused by the irregularly iced cross-section. The variable cross-section of the cable with ice became strongly nonsymmetrical with average dimensions of 0.192 m in height and 0.181 m in width.

Immediately after the icing process, the shape of the iced cable model was captured by a photogrammetry method. Using a numerical image analysis, a three-dimensional (3D) numerical model of the iced cable was obtained (Fig. 2a). For aerodynamic investigations the new iced cable model, shown in Fig. 2b, was made of polylactide plastic at a scale of 1:1.6 using a 3D printing procedure. The average outer dimensions of the model cross--section were 0.120 m in height and 0.113 m in width while the model length was 0.435 m. The detailed descriptions of the icing process, the final icing effect and preparation of the new iced cable model for the wind tunnel investigations are presented in a previous paper [7].

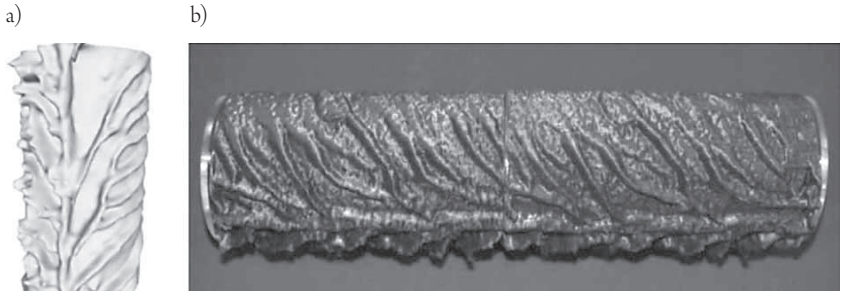

Fig. 2. (a) Three-dimensional numerical model of the iced cable in a scale 1:1, and (b) iced cable model created using a 3D printing method for the aerodynamic investigations

3. Experimental set-up of aerodynamic investigations

The tests were conducted in the aerodynamic section of the wind tunnel. This section has a rectangular cross-section with a height of 1.8 m, a width of 1.9 m, and a length of 11.0 m. The aerodynamic investigations of the iced cable model were performed with respect to determining three mean aerodynamic coefficients, i.e. drag, lift and moment coefficients as functions of *Re*. The tests were conducted for three principal configurations of the ice cable model in relation to the flow direction which are presented in Fig. 3. In this figure, the reference dimension *d* defined as the span-averaged outer dimension of each model configuration perpendicular to the airflow direction is shown.

Measurements of aerodynamic forces were made using the three-component aerodynamic force balance based on the electric resistant wire strain gauges which are able to measure drag, lift and moment forces, simultaneously. Six strain gauges of type Megatron KM102 were used with an operative range from 0 to 100 N at a temperature range of –10°C to 40°C, and with a declared nonlinearity of the sensors of 0.04%. Strain gauges were connected to the Dewetron acquisition system type DEWE-801-TR.

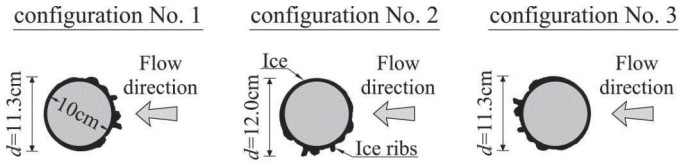

Fig. 3. Model configurations and the reference dimension *d* defined as the span-averaged outer dimension of the model, perpendicular to the airflow direction considered for the aerodynamic investigations

The sectional model was fixed motionlessly (in both support points the movement of the model was blocked in each direction) with the force balance in a horizontal position at a level of 69.3 cm above the floor of the aerodynamic section, crosswise to the airflow. Two sides of the force balance frame were equipped with plexi-glass end-plates to ensure a two-dimensional flow around the model. The sketch of the experimental set-up in the aerodynamic chamber is shown in Fig. 4.

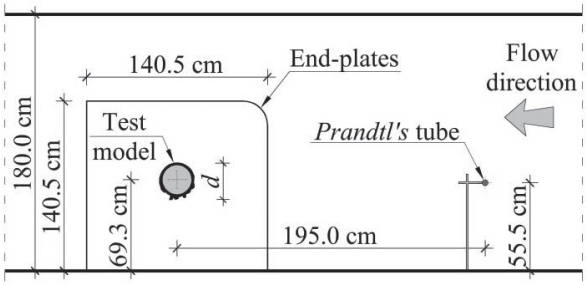

Fig. 4. Sketch of the experimental set-up in the aerodynamic section (view along the section)

The aerodynamic coefficients were investigated according to the following methodology. During the tests, the free stream velocity $\overline{u}^P$ was measured by *Prandtl's* tube placed upstream of the model centerline at a distance of 195 cm, i.e. in front of the force balance, and at a level of 55.5 cm above the floor of the aerodynamic section. Simultaneously, three radial forces acting on the iced model, i.e. drag, lift and moment forces were measured on both ends of the model by the three-component aerodynamic force balance (Fig. 5). For each model configuration, three time series of measurements at each mean free stream velocity $\overline{u}^P$ were made during the 60 s interval with a sampling rate of 100 Hz.

Due to the reduction of the flow area in the aerodynamic chamber by the presence of the force balance, the increase of the air flow velocity acting on the model between the end-plates of the balance, was observed as the blockage effect. In order to recognize the influence of this phenomenon on the test results, it was necessary to determine the reference wind velocity $\overline{u}_{ref}$ acting on the test model, i.e. the wind velocity measured in the undisturbed flow in the vicinity of the front of the model, between the end-plates of the force balance.

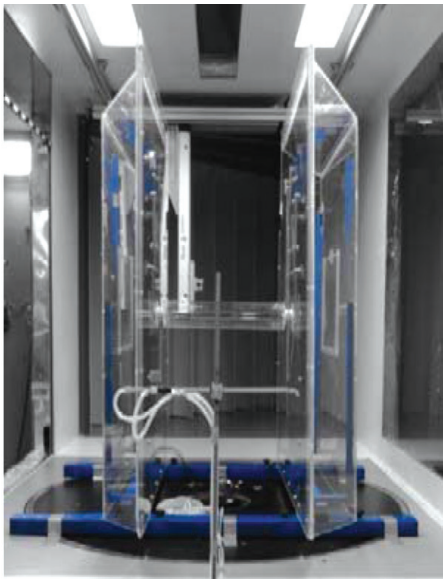

Fig. 5. View of the aerodynamic force balance in the aerodynamic section

The reference value of the wind velocity should be taken into consideration in the calculation of the aerodynamic coefficients of the iced model. For this purpose, the definition of the correction factor γ of the wind velocity was introduced in the following form:

$$\gamma = \frac{\overline{u}_{sr}^{T}}{\overline{u}^{P}}, \tag{1}$$

where: $\overline{u}^{P}$ is the time-averaged free stream velocity upstream of the force balance, i.e. in the position of *Prandtl's* tube reference, and $\overline{u}_{sr}^{T}$ is the time and span-averaged wind velocity along the longitudinal axis position of the test model in the undisturbed flow between the end-plates of the balance.

The time- and span-averaged wind velocity $\overline{u}_{sr}^{T}$ was determined according to the formula:

$$\overline{u}_{sr}^{T} = \frac{\sum_{i=1}^{n} \overline{u}_{i}^{T}}{n}, \tag{2}$$

where $\overline{u}_{i}^{T}$ is the time-averaged wind velocity recorded at the *i*-th measurement point along the longitudinal axis position of the test model, in the undisturbed flow between the end--plates of the force balance and *n* is the total number of measurement points.

In order to calculate the correction factor γ, the 30-second mean wind velocities $\overline{u}^{P}$ and $\overline{u}_{i}^{T}$ were measured by CTA (Constant Temperature Anemometry) sensors using two hot-wire anemometers simultaneously. During the tests, one reference CTA sensor was fixed in the position of the *Prandtl's* tube, while the second one was moved step by step from measurement point No. 1 to point No. 21. The locations of the measurement points were adjusted within a 2 cm distance along the longitudinal axis of the iced model. Fig. 6 depicts the locations of the measurement points along the longitudinal axis of the model between the end-plates of the balance. With every rearrangement of the rover CTA, i.e. at each measurement point, six series of measurements were performed at the free stream velocity $\overline{u}^{P}$ from 5.0 m/s to 16.3 m/s.

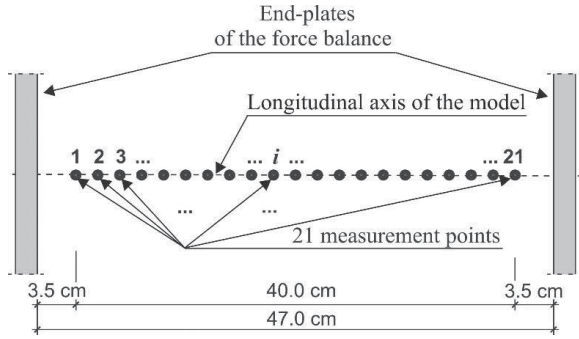

Fig. 6. Locations of measurement points along the longitudinal axis of the iced cable model between the end-plates of the force balance

Fig. 7 shows the measured distributions of time-averaged wind velocities $\overline{u}_i^T$ along the iced model axis position for six various time-averaged free stream velocities $\overline{u}^P$. It should be noticed that streamwise velocity is not symmetrically distributed along the horizontal line over the width of the test section. This is possibly due to the flow separation and pressure drop in the cross-section of the closed-circuit wind tunnel as a result of the air flow through the ducts joined together at an angle of 90° [9].

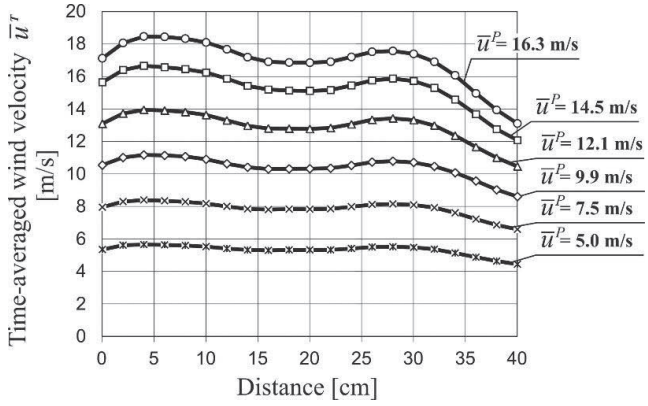

Fig. 7. Distributions of time-averaged wind velocities $\overline{u}_i^T$ along the iced model axis position for six time-averaged free stream velocities $\overline{u}^P$

The values of correction factor γ corresponding to the mean free stream velocities $\overline{u}^P$ within the range of 5.0 to 16.3 m/s were constant and were equal to $\gamma = 1.06$. It means that the blockage effect caused a 6% rise in $\overline{u}_{sr}^T$ in comparison to $\overline{u}^P$.

One should be aware that the blockage ratio computed as the total surface area of the model as well as the end-plates of the force balance, projected normally to the free stream velocity, divided by the total area of the aerodynamic chamber cross-section, was about 15%. Therefore, in this case the correction factor γ including the blockage effects was crucial for the present study and was taken into account in the calculations of the mean aerodynamic coefficients.

The reference wind velocity $\overline{u}_{ref}$ acting on the iced model was determined from the formula:

$$\overline{u}_{ref} = \overline{u}^P \cdot \gamma. \tag{3}$$

The *Re* values, corresponding to $\overline{u}_{ref}$, were evaluated according to the formula:

$$Re = \frac{\rho \cdot d \cdot \overline{u}_{ref}}{\mu}, \tag{4}$$

where: $\overline{u}_{ref} = 1.06 \cdot \overline{u}^P$,

$$\rho = \frac{P}{R \cdot T} \cdot 100 \tag{5}$$

is the air density, kg/m^3; P is the atmospheric pressure of the air, hPa; R = 287 m^2/(s^2 · K) is the gas constant; T is the air temperature, °C,

$$\mu = \mu_0 \left(\frac{T}{T_0} \right)^{0.76} \tag{6}$$

is the dynamic viscosity of the air, Pa · s; $\mu_0 = 17.1 \cdot 10^{-6}$ Pa · s, and T_0 = 273 K.

During the tests, the airflow was modeled with a turbulence intensity of order 5%. In order to calculate accurate Re values, the actual air temperature T and the atmospheric pressure of the air P inside the aerodynamic section were measured continuously. During the tests, the mean air temperature was about 27°C and the atmospheric pressure was equal to 957 hPa. The investigations were carried out at twelve sequential free stream velocities in a range between 3.6 m/s and 18.9 m/s, corresponding to the twelve *Re* number regimes in the interval $Re = 2.5 \cdot 10^4$ to $13.6 \cdot 10^4$.

4. Experimental results

The mean aerodynamic coefficients, i.e. drag C_D, lift C_L and moment C_M coefficients were calculated regarding the measured, 60-second averaged aerodynamic forces acting on the total surface area of the test model, projected normally to the free stream velocity taking into account the reference wind velocity $\overline{u}_{ref}$. The aerodynamic coefficients were calculated according to the following formulas:

$$C_D = \frac{\overline{F}_D}{0.5 \cdot \rho \cdot \overline{u}_{ref}^2 \cdot d \cdot l}, \tag{7}$$

$$C_L = \frac{\overline{F}_L}{0.5 \cdot \rho \cdot \overline{u}_{ref}^2 \cdot d \cdot l}, \tag{8}$$

$$C_M = \frac{\overline{F}_M}{0.5 \cdot \rho \cdot \overline{u}_{ref}^2 \cdot d^2 \cdot l}, \tag{9}$$

where: $\overline{F}_D$, $\overline{F}_L$, $\overline{F}_M$ are the 60-second averaged aerodynamic drag, lift and moment forces, respectively, d is the span-averaged outer dimension of the model perpendicular to the airflow direction (Fig. 3), and l is the length of the model equal to 0.435 m.

In order to validate the performance of the aerodynamic investigations, the tests for a circular smooth cylinder with a diameter of 10 cm were conducted first. In this case, the experimental set-up was arranged in the same manner as in the case of the iced cable model.

During the tests, Re was in the range from $2.8 \cdot 10^4$ to $13.2 \cdot 10^4$, i.e. within the subcritical range of *Re* for the circular smooth cylinder. Fig. 8a shows the measured mean aerodynamic drag force as a function of the reference wind velocity $\overline{u}_{ref}$, while Fig. 8b shows the mean drag coefficient as a function of *Re* for the circular smooth cylinder.

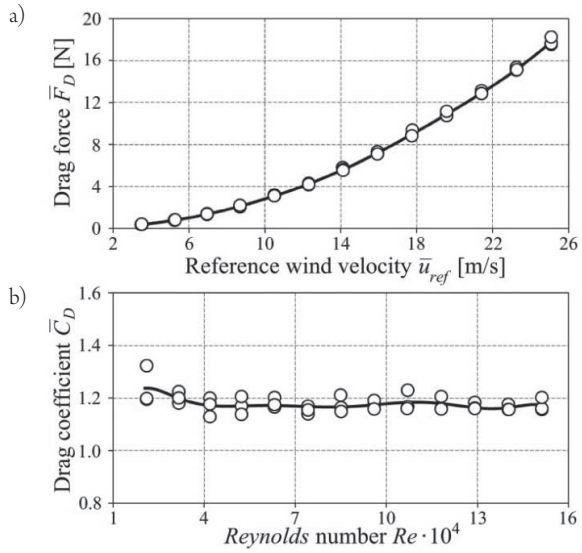

Fig. 8. (a) Variation of the mean aerodynamic drag force $\overline{F}_D$, with the reference wind velocity $\overline{u}_{ref}$, and (b) variation of the mean aerodynamic drag coefficient C_D with the *Re* number for the circular smooth cylinder

The obtained values of the aerodynamic drag coefficient C_D were changing from 1.13 to 1.22 for almost the entire range of *Re* that was studied. Only at a lowest value of $Re = 2.8 \cdot 10^4$, was the C_D coefficient slightly more than 1.3. Based on the results, it can be stated that the measured C_D values around 1.2 correspond well with the value reported by Schewe [11] and provided by the Eurocode Standard [3]. Thus, the preliminary results confirmed the validity of the adopted research methodology.

The mean values of each aerodynamic force and coefficient, obtained from three time series of measurements, were approximated and are shown as a continuous (for configuration No. 1), dashed (for configuration No. 2) and dotted (for configuration No. 3) lines in Figs 9, 10 and 11. The approximated values were taken further as the resulting values. Figs 9a, 10a and 11a depict the dependence of the measured and approximated mean aerodynamic forces, i.e. drag $\overline{F}_D$, lift $\overline{F}_L$, and moment $\overline{F}_M$, respectively, on the reference wind velocity $\overline{u}_{ref}$ for three considered configurations of the ice cable model in relation to the flow direction. Figs 9b, 10b and 11b depict the dependence of the measured and approximated mean aerodynamic coefficients, i.e. drag C_D, lift C_L and moment C_M coefficients, respectively, on the *Re* number for three principal configurations of the ice cable model.

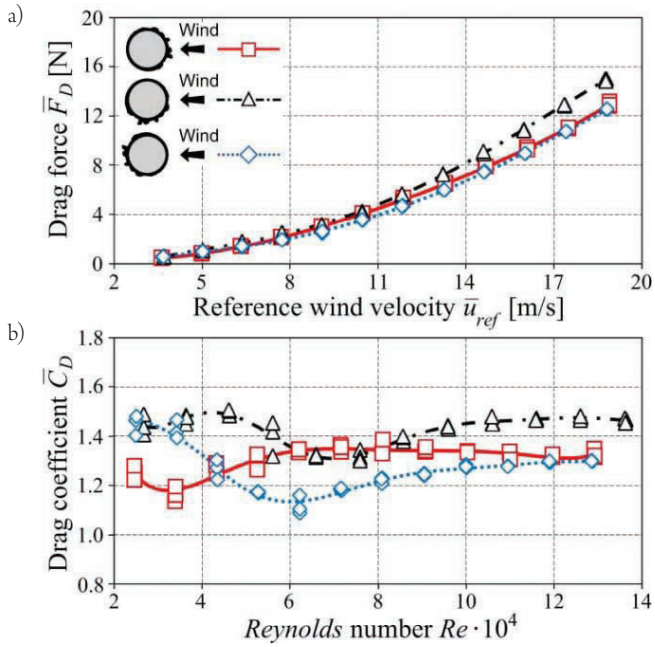

Fig. 9. (a) Mean aerodynamic drag force $\overline{F}_D$, versus the reference wind velocity $\overline{u}_{ref}$, and (b) mean aerodynamic drag coefficient C_D versus *Re* of the ice cable model for three principal angles of wind attack (configuration No.'s 1, 2 and 3)

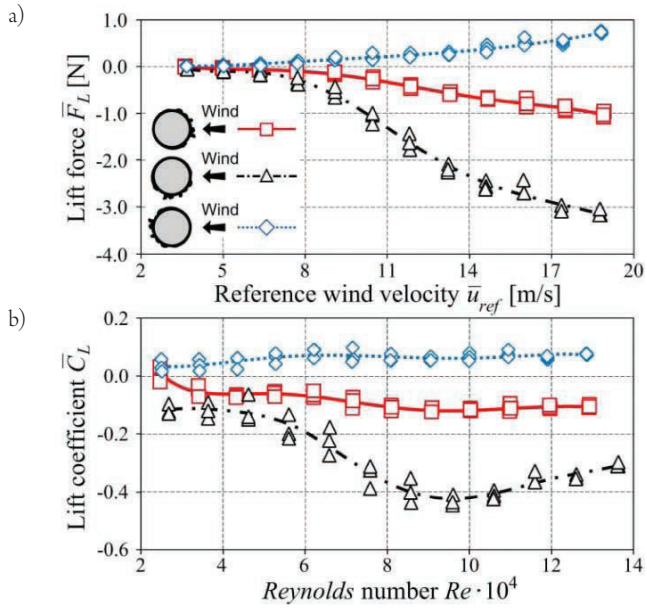

Fig. 10. (a) Mean aerodynamic lift force $\overline{F}_L$ versus the reference wind velocity $\overline{u}_{ref}$, and (b) mean aerodynamic lift coefficient C_L versus *Re* of the ice cable model for three principal angles of wind attack (configuration No.'s 1, 2 and 3)

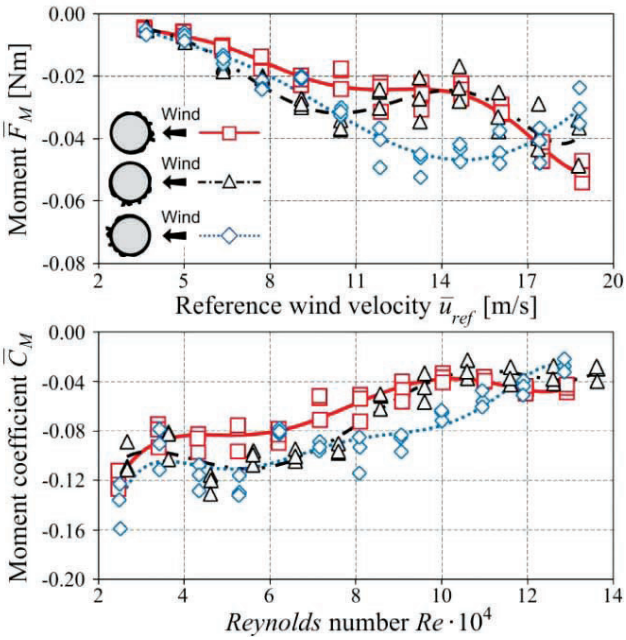

Fig. 11. (a) Mean aerodynamic moment $\overline{F}_M$ versus the reference wind velocity $\overline{u}_{ref}$, and (b) mean aerodynamic moment coefficient C_M versus Re of the ice cable model for three principal angles of wind attack (configuration No.'s 1, 2 and 3)

5. Concluding remarks

The experimental icing process of the inclined cable model of the cable-supported bridge was carried out in the Climatic Wind Tunnel Laboratory of the Czech Academy of Sciences in Telč. As a result of the icing process, the cross-section of the cable model became asymmetric and irregular with the rounded edges of the ice ribs accreted on the bottom side of the model and with a quasi-circular shape on its upper part. Then, it was clearly proved that the ice accretion on the cable model has a significant influence on the aerodynamic forces acting on the model. The airflow around the iced cable model is asymmetrical in relation to oncoming flow and there was an asymmetrical distribution of wind pressure on its surface. This phenomenon has been ascertained experimentally by measuring three components of the aerodynamic forces acting on the iced model. In the case of the circular cylinder, only the aerodynamic drag force is presented. Three mean aerodynamic coefficients, i.e. drag, lift and moment coefficients were investigated for the stationary iced cable model within the range of Re between $2.5 \cdot 10^4$ and $13.6 \cdot 10^4$. The aerodynamic investigations were conducted under the assumption that the mean wind direction during the icing process is independent of the wind direction during the investigations of aerodynamic coefficients. Therefore, the aerodynamic investigations were conducted with respect to three principal configurations of the model cross-section with respect to inflowing wind direction, namely for configuration No.'s 1, 2 and 3 (Fig. 3), each being perpendicular to the longitudinal axis of the cable model.

The determined values of the mean drag coefficient C_D for all considered model configurations depends on *Re* (Fig. 9b). For configuration No. 1 C_D varied in a range from 1.13 to 1.39. The lowest values of C_D were identified in the *Re* range of $2.5 \cdot 10^4$ and $4.3 \cdot 10^4$. In the remaining *Re* range, the C_D values changed slightly in the range from 1.26 to 1.39. For configuration No. 2, the C_D values were from 1.30 to 1.50 and the lowest values were in the range of *Re* from $5.6 \cdot 10^4$ and $8.6 \cdot 10^4$. $C_D = 1.2$ was used as a reference for the smooth circular cylinder and all the C_D values obtained for configuration No. 2 were higher than $C_D = 1.2$ by about 8% to 25%. In the case of configuration No. 3, the C_D values were within the range of 1.09 to 1.48, with the highest values for *Re* from $2.5 \cdot 10^4$ to $3.4 \cdot 10^4$. In the range of *Re* from $3.4 \cdot 10^4$ and $6.2 \cdot 10^4$, the C_D values decreased from 1.4 to 1.09. For *Re* greater than $6.2 \cdot 10^4$, C_D was slightly increased to 1.30.

The mean lift coefficient C_L determined for configuration No. 1 and 3 seems to be independent of *Re* in the range that was studied (Fig. 10b). For configuration No. 1, C_L varied in the range from 0.06 to –0.13 (the change of sign indicates the change in direction of the lift force acting on the model), while for configuration No. 3, C_L varied in the range from 0.03 to 0.10 for the entire range of *Re* that was studied. The highest absolute values of C_L were found in the case of configuration No. 2 within the range from –0.09 to –0.44, however, the greatest values were in the range of *Re* from $7.6 \cdot 10^4$ to $12.6 \cdot 10^4$.

The mean moment coefficient C_M determined for all configurations strictly depends on *Re* (Fig. 11b). For all configurations, the C_M values increased slightly from –0.13 to –0.02 for the entire range of *Re* that was studied.

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Light pollution as an environmental hazard

Zanieczyszczenie świetlne jako zagrożenie środowiskowe

Abstract

Light pollution is one of the most widespread but at the same time least noticeable environmental hazards resulting from human activity. It is defined as disturbing the nocturnal environment with light emitted by anthropogenic sources. Light pollution is described as the glare, the trespass, and the sky glow resulting from the scattering of artificial light in the atmosphere. The paper analyses the impact of these three categories on the environment. The results of the long-term research on this problem are presented. It was found that the largest impact on the environment, both direct by the glare and indirect by the sky glow, result from lamps with spherical shields and LED advertising billboards. The possible influence of light pollution on the eutrophication of reservoirs was also researched.

Keywords: light pollution, glare, sky glow, eutrophication

Streszczenie

Zanieczyszczenie świetlne jest jednym z najpowszechniejszych, lecz jednocześnie najmniej zauważalnych zagrożeń środowiskowych. Jest ono rozumiane jako zaburzanie nocnego środowiska naturalnego światłem emitowanym przez źródła antropogeniczne. Przejawia się poprzez: olśnienie, zaświecanie oraz łunę świetlną, powstającą wskutek rozpraszania sztucznego światła w atmosferze. Przedstawiono wpływ wymienionych kategorii zanieczyszczenia świetlnego na środowisko naturalne. Zaprezentowano wyniki własnych badań tego zagadnienia. Stwierdzono, że największy wpływ, zarówno bezpośredni poprzez olśnienie, jak też pośredni, poprzez łunę świetlną, mają lampy z kulistymi osłonami oraz reklamowe tablice LED. Zbadano również możliwy wpływ zanieczyszczenia świetlnego na eutrofizację zbiorników wodnych.

Słowa kluczowe: zanieczyszczenie świetlne, olśnienie, łuna świetlna, eutrofizacja

1. Introduction

Light pollution, known also as photopollution, is one of the more burdensome and, at the same time, one of the most unnoticed environmental hazards. Usually, it is defined as the nuisance of artificial lighting caused by an excess of light coming from improperly designed light sources. However, there are many other more or less detailed definitions. The phenomenon was described for the first time by astronomers in the mid-1970s as light pollution [4, 40], defined only as the brightening of the night sky due to artificial lighting. At this time, the impact of light pollution on ecosystems had already been noticed, and in the 1980s, the notion of photopollution was introduced as the degradation of the natural environment by artificial lighting [39].

2. General concept of light pollution

2.1. Forms of light pollution

According to the classification introduced in 1988 by the International Dark-Sky Association [13], light pollution may occur in the following forms:

- The glare when the light source is directly visible and the contrast between it and the surroundings causes disturbance to the nocturnal vision of living organisms is one such form of light pollution. Examples are brightly lit ski slopes in winter, street lighting, and especially various types of illuminated advertising installations, mainly LED billboards rapidly changing their brightness;
- Trespass, treated as a violation of property boundaries, constitutes another form of light pollution. It occurs when the light source illuminates not only the dedicated area, but also the surrounding area. A typical example is the light of exterior street lamps illuminating the interiors of flats through the unprotected windows. Another example may be lamps intended to illuminate roads leading through the National Parks and other protected areas illuminating the surroundings and, in doing so, disturbing the local nocturnal ecosystems;
- Grouping of light is the form of light pollution in which the number of light sources in a given area exceeds the needs. This phenomenon often occurs in tourist areas, because the overlapping illumination coming from brightly glowing lamps is often treated as a decorative element. Such grouping of lamps also constitutes sources of light pollution in the previously mentioned categories. In urban areas, this kind of light pollution sometimes occurs in parks or university campuses. However, it can also be found in the vicinity of recreation centres located near or even inside the National Parks, reserves and other protected areas. This type of light pollution is especially visible in the case of lighting of sports facilities – sports fields, ski slopes, etc.;
- Sky glow is a form of light pollution resulting from the dispersion of artificial light on atmospheric aerosols. This is the most widespread category of light pollution as such

dispersed light even reaches areas where none of the previously mentioned categories of light pollution are present. The sources of sky glow are improperly shielded lamp filaments or wrongly inclined lamp holders. Every single such light induces a local sky glow effect, which is important particularly in National Parks, reserves and other protected areas. However, it should be emphasised that exceptionally strong sources of this kind of light pollution are city glows, which have an impact upon and disturb even distant nocturnal ecosystems.

2.2. The scale of the problem

The negative impact of artificial lighting on the environment had already been noticed as early as the nineteenth century [11, 26]. However, until the second half of the twentieth century, it seemed that this effect was minimal and limited only to certain specific environments [24].

Starting from 1950s, the rapid development of urbanisation, as well as the emergence of inexpensive sources of light, made it difficult to find areas of natural nocturnal darkness in densely populated areas on Earth. The main problem has become the sky glow, caused by the uncontrolled emission of light to the sky [38]. Satellite images show that the main such light-polluted areas are the eastern states of the USA, Central and Western Europe and Japan. Analysis of archival measurements of the brightness of the night sky led to the conclusion that from the early 1990s, only Białostocczyzna (NE Poland) and the Bieszczady Mountains (SE Poland) show no increase in this quantity among the researched areas of Poland. In other cases, especially in large cities, a rapid increase in the sky glow surface brightness has been observed since the end of the 1990s [36]. Recently, Kyba et al. have shown a worldwide increase in brightness and lit area using VIIRS DNB data [20]. Until the middle of the twentieth century, it was believed that the only disadvantageous effect of the sky glow was its interference with astronomical observations. As a result, it was mainly astronomers who were interested in this phenomenon; of course, they only researched the glow of the cloudless sky. However, the glow of an overcast sky in the presence of light pollution sources is much brighter so, in this case, it has a significant environmental impact. This aspect of light pollution has only recently received attention [18, 35]. Analysis of the Light Pollution Atlas [9] and VIIRS satellite data [32] combined with the results of measurements made by the Light Pollution Monitoring Laboratory at Cracow University of Technology [35, 36] leads to the thesis that approx. 85% of Poland's surface is threatened by light pollution in the form of sky glow. In these areas, the luminance of a clear and cloudless sky exceeds the natural level of 0.21 mcd/m^2. About 7% of Poland's surface is light polluted to a high extend with sky luminance exceeding 1.09 mcd/m^2, which is over five times the natural level. Ground illumination from such a bright sky significantly exceeds the natural luminance caused by a quarter moon (0.63 mcd/m^2) [38]. The most light-polluted areas in Poland are primarily the Silesian agglomeration, the surroundings of Gdańsk-Sopot-Gdynia, Łódź, Warszawa and Kraków, but there is also light pollution in the surroundings of each smaller town. Extending the previously accepted categorisation of light polluted areas [36], it can be concluded that the following areas belong to individual categories: A – large, industrialised cities (e.g. Kraków, Warszawa), B – medium or small cities in industrialised areas (e.g. Lublin, Szczecin,

Niepołomice), C – medium-sized or small towns in medium-industrial areas or distant suburbs of large cities (e.g. distant suburbs of Lublin, Szczecin or Elbląg), D – medium or small towns in poorly industrialised areas (e.g. Krosno, Białystok), E – uninhabited or sparsely populated areas, located in non-industrialised areas (e.g. Bieszczady, Polesie Lubelskie, Puszcza Augustowska). The most important factor here is not the population, but its density, which should be associated with the effect of grouping the light sources and the superposition of the light coming from them. It seems that up to a population density of around 200 inhabitants/km^2, the impact of surface light sources on the brightness of the sky glow is negligibly small [38].

2.3. The environmental impact of light pollution

Among the many negative phenomena associated with the described problem, one can mention, in particular, the disturbance of nocturnal migrations, naturally guided by such sources of light as the moon or the stars of some constellations [1, 7, 30]. Migration disorder may consist of confusion through surface light sources misidentified as the moon, as well as blinding birds by bright light sources causing degradation to the nocturnal adaptation of their eyes. Probably even the glows of cities they pass prevent the identification of constellations of stars known to birds.

Birds are often victims of collisions with bright, illuminated windows [5]. This is especially true for office buildings, often built with glass technology. Such a bright glass wall blinds birds at night and confuses them. As part of the FLAP program [10] during each of the three--month migration seasons of 1993–1995, more than 5,000 birds from 158 species, who were victims of such collisions, were collected in the Toronto (Canada) office district, of which 64 species are on the list of endangered species. It is estimated that every year, at least one million night migrating birds perish in this city.

Artificial lighting also disturbs the reproductive cycles of many animals, mainly amphibians such as frogs and salamanders, as well as insects [28]. This negative effect was also found among mammals, including lemurs [21]. This poorly researched negative impact of light pollution directly affects night ecosystems, causing in particular, an increase in the rate of the extinction of certain species. Night lighting, both direct as well as through the sky glow, often disturbs the hunter-victim balance, for example, by extending the period of activity of migratory falcons into the night [23]. Other examples of the negative effects of light pollution are found in the ecosystems of reservoirs [25], where the artificial lighting of the water surface affects the vertical migration of zooplankton. This is the reason for its deficit in reservoir surface layers, just as occurs during the full moon [15]. In the case of the constant artificial lighting of the water surface, both direct through local lighting, as well as through the sky glow of nearby cities, zooplankton always avoids feeding in the subsurface layers of the reservoir; this could cause the growth of phytoplankton and, as a result, eutrophication [38]. It was also found that artificial light at night changes the daytime behaviour of certain species of fish [17].

The health implications of light pollution should also be considered [29]. Night lighting inhibits the production of melatonin in the human body which leads to sleep disorders. This, in turn, increases the risk of developing various types of diseases, both psychological (depression) and somatic (including cancer).

2.4. Sources of light pollution

The causes of light pollution are all improperly constructed light sources, most often street, park and residential lamps [2, 8, 35]. In many cases, the problem is not so much the kind of light source or its brightness as the construction of the cover or inclination of the shield to the plane of the horizon. Older models of street lamps with a convex cover of the light source which, in addition to illuminating a dedicated object (road, pavement, parking), also send a large part of the luminous flux above the horizon. This in turn causes not only dazzling of animals and people, but also contributes to the local sky glow. Nowadays, it is recommended to use lamps with a flat cover. However, even such a solution can be a source of sky glow when the lamp shield is not parallel with the line of the horizon.

Extreme negative examples of lighting are lamps with ball-shaped covers and other decorative lamps, often found in parks and housing estates. These lamps direct most of their light sideways and upwards. At the same time, the opaque base of the cover casts a shadow on the ground, resulting in insufficient lighting of the surface under the lamp. Sometimes, often for decorative purposes, sets of several such covered lamps are created, forming a composite lamp. Such lamp, although correctly illuminating the surface, significantly increases the glare effect and also contributes very much to the sky glow. Sometimes, reflected street lamps are used. In this case, the light is directed upward to a mirror, which then reflects the light to the ground. The advantage of this kind of lighting is the lack of a dazzling effect. However, unfortunately, a large proportion of the light stream often bypasses the mirror resulting in a significant contribution to the sky glow.

Other types of light pollution sources are advertising boards (billboards), which can be both illumined externally and self-illuminated (LED boards) [22]. In the first case, light pollution is generated by models with bottom lighting, often with individual reflectors. In this case, light, both reflected from the board as well as passing it, contributes to the sky glow. LED boards, often rapidly changing in their brightness, cause glare in addition to contributing to the sky glow. This not only constitutes a threat for drivers, but is also the cause of disturbance to the neighbouring night ecosystems.

It should be noted that illumination of monuments also often contributes to an increase in brightness of the sky glow [31].

3. Results of the measurements

3.1. Measuring instruments

The measurements of light intensity were performed using the Sonopan L-52 high--sensitivity lux meter. The lux meter has four sensitivity ranges: 1–2000 lx, 0.1–200 lx, 0.01–20 lx and 0.001–2 lx. The experimentally determined accuracy of measurements for these ranges was 3, 0.3, 0.03 and 0.003 lx, respectively. Measurements of illuminance from distant sources were made using a diaphragm enabling the isolation of such sources from the environment.

The sky glow is the extend object like comets, nebulae or Milky Way. Since the light from any extended object is spread out over some area of the sky, astronomers measure their surface brightness. The surface brightness is a measure of brightness per area on the sky. Measurements of the sky glow surface brightness (S_a) were made using specialised sky quality meters (SQM), giving the results in units of surface brightness commonly used in astronomy: magnitude per square arc second (mag / arcsec^2) [12]. This is a logarithmic and inverse scale, i.e. higher S_a values mean darker sky, based on the human perception of the brightness of a luminous surface. There is no direct equivalent of these units in the SI system; however, to a certain extent they can be converted to the cd/m^2 units of luminance or mcd/m^2 in low light. The commonly used formula for conversion of these units is [6]:

$$[\mathrm{cd/m^2}] = 108930 \cdot 10\text{^}(-0.4 \cdot [\mathrm{mag/arcsec^2}]) \qquad (1)$$

The accuracy of the SQM guaranteed by the manufacturer is in the order of 0.1 mag/arcsec^2. However, the tests performed showed a S_a reading stability of 0.02 mag/arcsec^2 under stable atmospheric conditions.

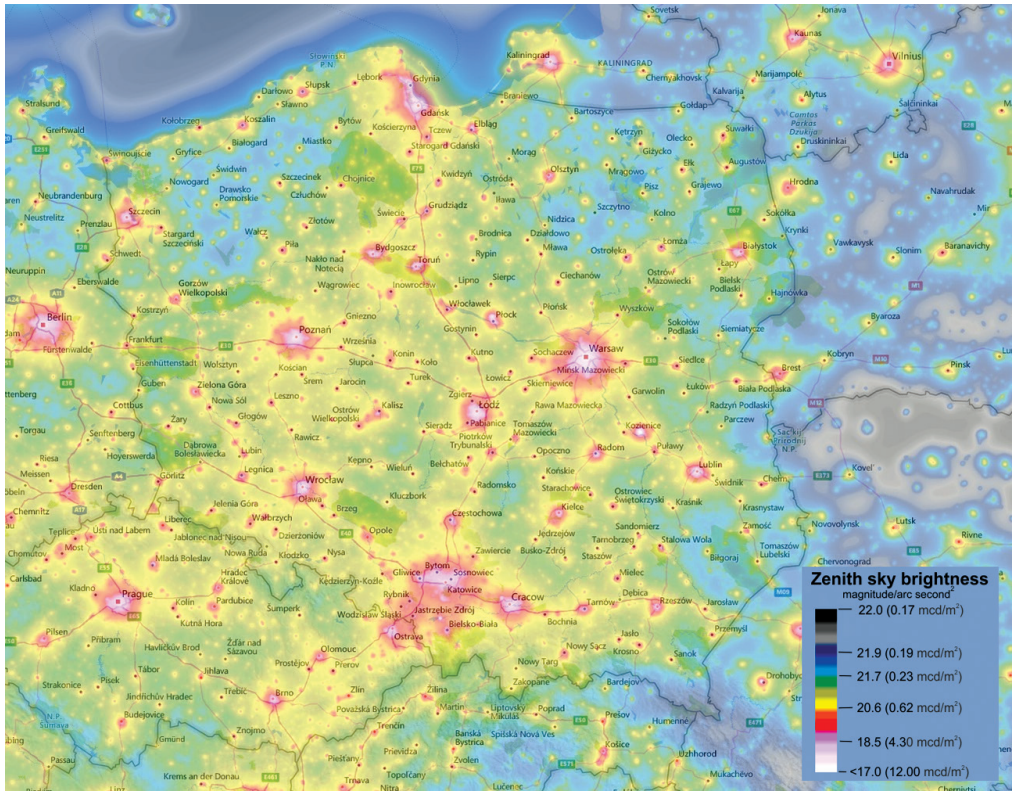

Fig. 1. Satellite map of the zenith sky brightness for the cloudless nights for Poland in 2015; the colours correspond to the modelled night sky surface brightness expressed in the astronomical units mag/arcsec^2 and also in the SI units mcd/m^2 (VIIRS/DMSP Earth Observation Group, NOAA National Geophysical Data Center, https://www.lightpollutionmap.info)

It should be noted that there is also a new method for nocturnal light providing spatially resolved full-spectrum radiance over the full solid angle using an all-sky camera [14] and it is planned for use in future research.

3.2. Researched cases

3.2.1. Direct lighting by artificial light sources

Measurements of illuminance of the ground as a function of distance from different types of lamps (Fig. 2) were made in three directions: towards the illuminated object (front), in the direction perpendicular to the previous direction (sideways) and in the opposite direction to the illuminated object (backlight). For some types of lamps, measurements were also taken vertically upwards, at a height of approx. 10 m above the lamp.

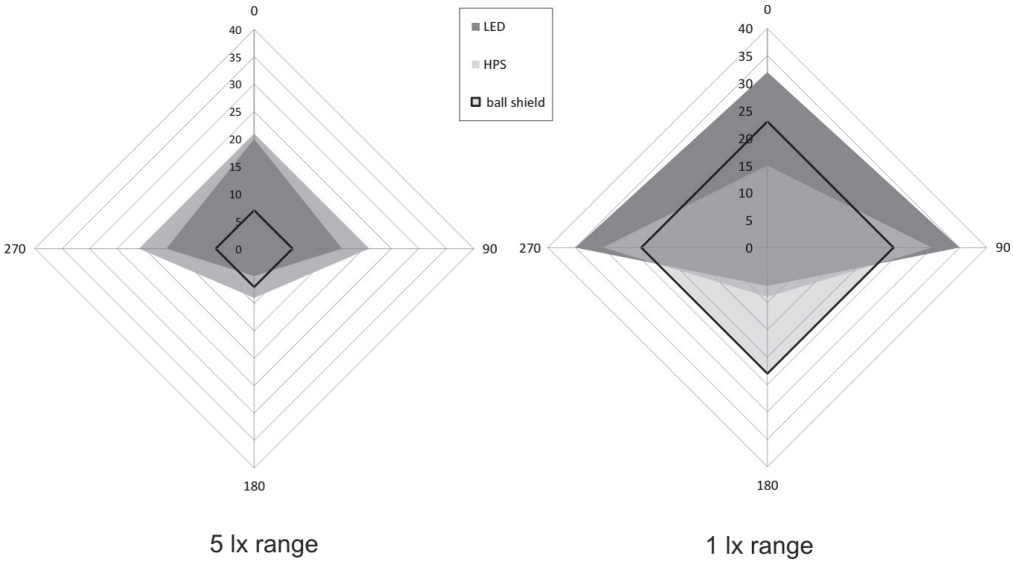

Fig. 2. Illuminance range spatial distribution (at the 5 lx level, on the left and at the 1 lx level, on the right) around several types of lamps – estate lamps with a transparent and white ball shields, street high pressure sodium lamps (HPS), street LED lamps; distance from the lamps is given in metres, the four cardinal directions are given in degrees, where 0 denotes the direction of the illuminated street and 180 denotes the opposite direction

In the case of a lamp with a transparent ball-shaped cover, the distribution of illumination around the lamp and above it turns out to be largely isotropic with the exception being a deficit in the illumination of the ground directly under the lamp. This effect is related to the shadow of the cover base on the ground. The maximum illuminance, approx. 10 lux, occurs at a distance of 5 m from the lamp. Illuminance from these kinds of lamps drops to a level of less than 0.2 lx at a distance of approx. 15 m. This is a value close to that of a full moon, so these lamps should not pose a threat to the near-surface areas of surrounding ecosystems. Moreover, they are seen from distances exceeding a dozen or so metres at low altitudes above the horizon. However,

considering that around 70% of the light coming from these kinds of lamps is directed above the horizon, they are one of the most significant artificial sources of light disturbing the ecosystems of flying animals. In particular, in the Ojców National Park and in Orawa, the concentration of various species of moths and bats hunting for them is observed around the street lamps, which is a significant violation of the hunter-victim balance [33].

Similar considerations apply to lamps with spherical translucent white covers. The only difference to the previously described lamps is that there is practically no shadow area under such lamps.

Measurements of illumination from high-pressure sodium lamps (HPS) and modern LED lamps showed its highest value in the axis of the illuminated street. This is, of course, consistent with the intended purpose of this kinds of lamps. Illumination in the direction of illuminated streets falls below 5 lux at a distance of 20 m from the lamp. This means that the road is properly illuminated across the whole of its width. Illumination in the perpendicular, sideways direction also reaches a limit value of 5 lux at a distance of about 20 m, which means that such spaced lamps should correctly illuminate the street. In the opposite direction, to the illuminated object, the level of backlight from the HPS lamps decreases to 5 lx at a distance of 10 m and only 5 m for LED lamps. From a distance of 7 m, the illumination from LED lamps ceases to be measurable.

The illuminance from a single house at a distance of 60 m is equal to 0.06 lx, from a single shining window at a distance of 20 m it is 0.08 lx, from a shopping centre at 2 km it is 0.018 lx, and at a distance of 600 m it is 0.03 lx , while from an isolated housing estate at a distance of 2 km it is 0.2 lx. Therefore, illumination in these cases is small, only in the latter case is it comparable with the maximum illuminance from a full moon (0.2 lx). Due to the fact that such distant sources of light are seen by ground-based living organisms at a low altitude above the horizon, they are effectively obscured by terrain and vegetation, and in this case, their direct impact on ecosystems should be considered to be insignificant. Such light sources, however, have an impact on the behaviour of bats, birds and insects active at night.

Much more threatening sources of light pollution in this category are advertising light boards, in particular LED boards with quickly changing brightness. Measurements show that at a distance of 12 m from this type of billboards, the illuminance often changes from 65 lx to 280 lx within a fraction of a second. Sometimes, illuminance changes even in the range from 15 lx to as much as 330 lx, which constitutes a more than twentyfold increase. In this case, the effect of glare is particularly important. It should also be noted that in this case, the maximum illuminance exceeds that of a full moon by a few orders of magnitude reaching a value similar to that from the setting sun on a cloudless day.

3.2.2. Illumination of the Earth's surface by the night sky glow

The measurements of the sky surface brightness and the ground illumination made on three positions enabled the determination of a strictly linear relationship between these two factors [16]. This enables estimation of the ground illumination even if only the S_a values are known.

Measurements of the surface brightness S_a of a clear and cloudless night sky revealed that the illumination of the ground through artificial light scattered in the atmosphere, even in a large city, does not exceed 0.01 lx. Such lighting should not directly affect the ecosystems. However, the surface brightness of such sky especially in the presence of particulate matter in winter, is comparable to the sky surface brightness at dusk. This, of course, can disturb the circadian rhythms of many organisms, including humans, by affecting their biological clocks [38].

The measurements of the sky surface brightness as a function of the degree of cloudiness were made in 2010-2016 in different environments (Fig. 3). They showed a clear positive correlation between these values. In the case of large cities, the surface brightness of the overcast sky reaches 16 mag/arcsec^2 and the corresponding ground illuminance exceeds 0.2 lx. This value is significantly greater than the measured ground illuminance by a full moon (0.1–0.2 lx), as well as the value of 0.1 lx given in the literature for our latitudes [3], and even is close to the value of 0.3 lx, which is given for tropical areas [19]. In the presence of snow cover, the sky surface brightness reaches a value close to that measured about an hour after sunset. Such illumination undoubtedly affects ecosystems, especially in the case of organisms which have a life rhythm regulated by the light of the moon. The yearly statistics of the sky surface brightness measured on moonless nights showed that in the centre of Kraków, as much as 38% of such nights is brighter than during a full moon period. In large estates and on the outskirts of the city, this value is 14–25% and 10%, respectively. It should be remembered that the moon is almost a point source of light, and furthermore, its elevation changes over

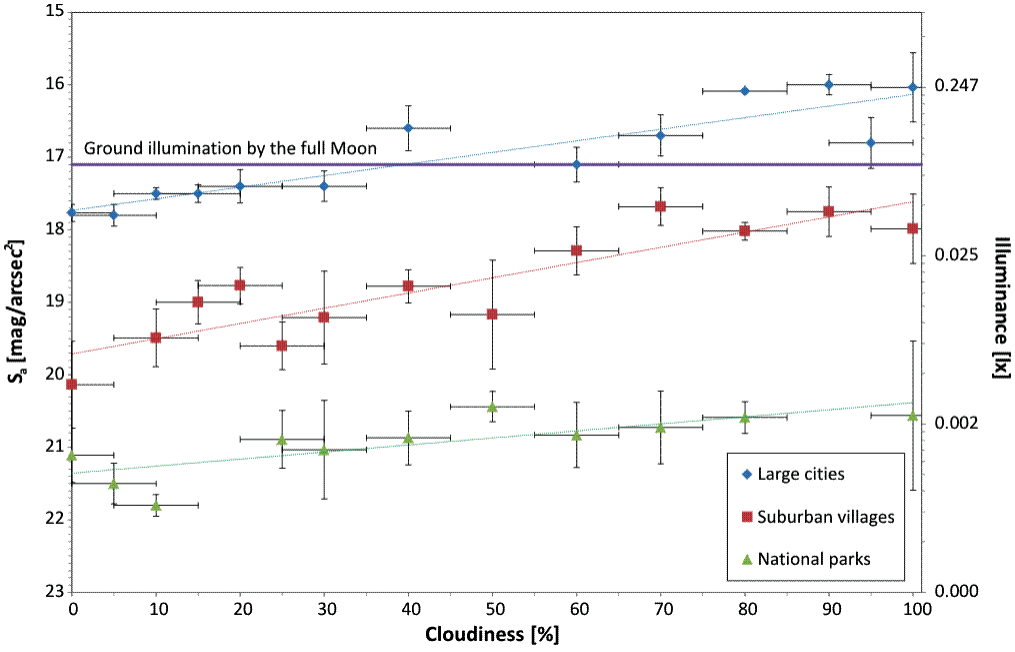

Fig. 3. The night sky surface brightness (S_a) and ground illuminance as a function of estimated cloudiness for three different environments; the horizontal line indicates the sky surface brightness giving the ground illuminance equal to that provided by a full moon

the course of the night, but the sky glow is visible all night, turning it into 'dusk'. This effect is not strictly related to the size of the settlement unit or its population, but rather to the density of light sources and thus, the density of the population. The sky surface brightness measured in the cities of Bielsko-Biała, Wadowice and Zakopane sometimes exceeds even that measured in Kraków [34]. In each case, the range of the 'light island', defined as the range of the measurable brightening of the sky at its zenith in comparison with the surroundings, reaches a distance of around 3 km from the border of the settlement unit.

3.2.3. The impact of sky glow on the eutrophication of reservoirs

The impact of the night-time lighting of the water surface on the reproduction and mobility of zooplankton is observed in literature [15].

In 2014–2016, measurements of the sky surface brightness were performed at the water intake of the Municipal Water and Sewerage Company in Kraków (MPWiK) on the Dobczyce Reservoir. These measurements enabled the analysis of the impact of the night sky surface brightness on the values of water quality indicators, measured at this position. The averaging of the night sky surface brightness on a time interval containing the local midnight, i.e. from 11:00 pm to 1:00 am, enabled the elimination of the effect of the variable length of twilight during the year.

Weekly reports from MPWiK give the values of the following water quality indicators for samples collected at three different depths (3, 10 and 15 m): temperature, turbidity, pH, dissolved oxygen, silica, dissolved phosphates, total phosphorus, Kieldahl nitrogen, BOD5 (biochemical oxygen demand), COD (chemical oxygen demand), suspension, conductivity, chlorophyll, phytoplankton and zooplankton (total) and the saprobic index. A clear periodicity of about 30 days, repetitive in each research year, is observable with regard to the following indicators: concentrations of phosphates, total phosphorus, and especially chlorophyll *a* and an abundance of phytoplankton and zooplankton. This periodicity is clearly correlated with changes in the sky brightness associated with the phases of the moon. It should be noted that values of these last mentioned indicators are directly related to the content of phytoplankton in water.

In the case of the Dobczyce Reservoir, the surface brightness of the night sky reaches values similar to that of the period of nautical twilight (S_a = 16.6 mag/arcsec^2). It was the cause for research of the correlations between the chlorophyll *a* content and the night sky surface brightness of the night sky in 2014–2015 (Fig. 4). Due to the different frequency of measurements of both quantities, monthly averages were analysed. Only the vegetation months were taken into account, i.e. those in which temperatures enabled the development of phytoplankton: seven months in 2014 and five months in 2015.

The calculated Spearman's rank correlation coefficients between the chlorophyll *a* content and the night sky surface brightness were –0.964 in 2014, –0.900 in 2015, and –0.909 for both years in total. As the quantity of analysed series of data was small, the critical values calculated with the use of randomisation tests [27] were used to assess the significance of these correlation coefficients. A one-sided permutation test was used. The correlation coefficient

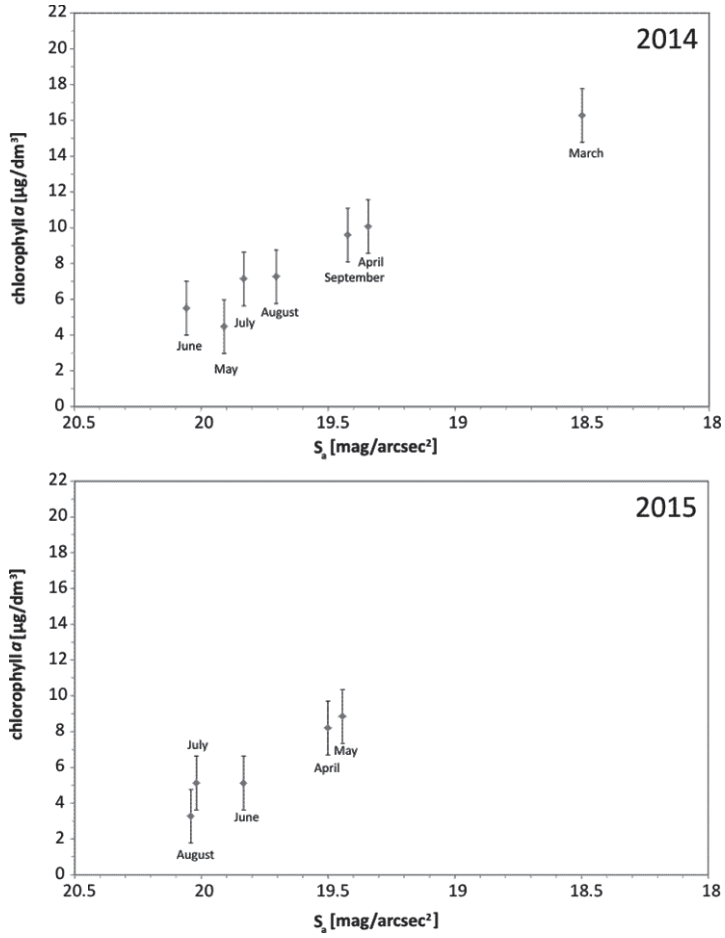

Fig. 4. Average monthly concentration of chlorophyll *a* in the surface layer of the Dobczyce Reservoir (3 m under the surface of the water) vs. the night sky surface brightness (S_a) in 2014 and in 2015

was equal to the critical value for the significance level $\alpha = 0.0025$ in 2014 and for $\alpha = 0.05$ in 2015. For both years together, the correlation coefficient was higher than 0.846, which is the critical value for the significance level $\alpha = 0.0005$. This means that the determined high correlations are significant, confirming the thesis of the impact of the night sky brightness on the chlorophyll *a* content. This is additionally confirmed by the impact of water turbidity on the correlation level observed in 2014 [37].

4. Summary and conclusions

The presented research shows that artificial, improperly shielded light sources should have only a small direct impact on terrestrial ecosystems. However, they cause disturbance of the hunter-victim balance in the case of pterofauna ecosystems. The problem concerns,

in particular, lamps with spherical shields. In this case, approx. 70% of the light is emitted above the horizon line, with the dominant vertical direction. The same light sources generate the night sky glow to a large extent. Such glow, especially in cities, has a major impact on ecosystems, both by creating the effect of unceasing twilight, and by illuminating the ground at night in conditions with an overcast sky. Moreover, the sky glow also affects the city's surroundings, directly disturbing the night ecosystems in the adjacent areas, mainly because the permanent full-moon light level masks the natural cycle of the moon. An example of such ecosystems is reservoirs, where both night lighting of the water surface by the light sources located on the shore (or, for example, the dam shaft), as well as by the glow coming from surrounding villages, can lead to eutrophication and, as a result, water quality deterioration.

To minimise the negative impact of artificial night lighting on the environment, it is necessary to:

- avoid the placement of various types of advertising boards, especially LED with variable brightness, near protected areas;
- install street lamps at such distances from the protected areas that outside the dedicated area, the ground illumination does not exceed that which comes from a full moon. The minimum distance, regardless of the type of lamp, can be specified at approx. 35–40 m;
- use appropriate shields which direct light only to the dedicated area – the impact of the direct light of such a lamp on the surroundings will then be minimised, and the brightness of the sky glow will also be reduced, and this particularly applies to cities located near protected areas.

These activities, in addition to having a positive impact on the environment, will give measurable economic benefits.

Further studies of the described problem are planned, in particular, with regard to the effect of the spectrum or colour of nocturnal light on the environment.

I would like to thank the employees of the Municipal Water and Sewerage Company in Kraków (MPWiK), especially to Mr. Jacek Stasik for the supervision of continuous measurements of the night sky brightness on the water intake in Dobczyce and to Mr. Tadeusz Bochnia for sharing weekly reports on water quality.

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Electrical power steering – modelling and bench testing

Elektryczne urządzenie wspomagające kierownicę – modelowanie i badania stanowiskowe

Abstract

The article presents a dynamic model of an electric device supporting the steering system of a passenger car; the model was verified through a series of bench tests. The research object was an integrated electric power steering system (EPS) mounted on a steering column and cooperating with a steering gear. The results of the theoretical analysis were compared with the results of tests performed on a specially built research bench fully reflecting the work of assistance in the car. A satisfactory level of agreement between the results of the model tests and the bench tests was obtained.

Keywords: EPS, modelling, bench tests

Streszczenie

W artykule przedstawiono zweryfikowany testami laboratoryjnymi dynamiczny model elektrycznego urządzenia wspomagającego kierownicę. Przedmiotem badań było zintegrowane elektryczne urządzenie wspomagające kierownicę (EPS) zamontowane na kolumnie kierownicy. Wyniki analizy teoretycznej porównano z wynikami testów przeprowadzonych na specjalnie zbudowanym stanowisku badawczym w pełni odzwierciedlającym pracę urządzenia w samochodzie. Uzyskano zadawalającą zgodność między wynikami badań stanowiskowych a wynikami analiz teoretycznych.

Słowa kluczowe: EPS, modelowanie, stanowisko badawcze

1. Introduction

The subject of this work is the development of an EPS device model and its verification with the results of bench tests. Workplace tests of an electrically supported passenger car steering system were conducted in order to determine the values of the stiffness, damping and friction parameters occurring in the assistance system. Harmonic measures were applied from the steering wheel and wheels.

The study of the EPS system includes the examination of both the control objectives and the control strategies. Control objectives relate to the size of the support system and to the feeling of the road. Control strategies are divided into classic strategies resulting from the drive automation and strategies using models developed separately.

The article [5] focuses on the development of a control algorithm and analyses the choice of simplifications applied when developing a control system to approximate the mechanical characteristics of a vehicle.

Articles [7, 9] present a simulation of the EPS control system integrated with the overall dynamic vehicle model. Co-simulation was used, i.e. the simultaneous cooperation of two software environments (ADAMS and Matlab) by means of a subprogram specifying data channels and running the ADAMS environment in each simulation clock. Using co-simulation, a multi-mass dynamic model of a vehicle cooperating with the EPS control algorithm was simulated on the smooth road with one inequality [7]. The author of article [9] presented a method of modelling the EPS system and its co-simulation in combination with the control system. The mechanical model was calibrated using the experimentally measured torsional stiffness of the torsion bar and the friction of the mechanism. The EPS model optimised in ADAMS was converted into Matlab/Simulink, and was then combined with the Simulink driver model. Co-simulation was performed and described for the frequency response test of the EPS device. The proposed method enables a good prediction of the dynamics of the EPS system and can be an effective way to optimise the EPS control system.

The authors of article [8] proposed two indicators – steering sensitivity and road feel – in order to assess the performance of the steering system. It was found that steering sensitivity depends on the following factors: stiffness of the torque sensor, the electrical characteristics of the propulsion engine, its moment of inertia, the transmission ratio of the power steering, the boost control and the vehicle parameters.

In [1], the authors considered the possibility of adjusting steering sensitivity; they used a simplified model of the steering system, containing both a reduced mechanical and an electrical model. The effectiveness of the adopted simplification has been proven by computer simulation.

Of the many methods of torque control of an electric motor used in EPS systems, the authors of article [2] drew attention to the method of selecting the moment consisting of minimising the difference between the values of the standard moment and the measured moment. The process of designing a controller which realises the algorithm of minimising the mentioned difference is presented. During the tests, the discontinuity of the steering torque was analysed due to the fact that this moment occurs both with and without assistance. It has

been *surmised* that the cause of discontinuity is the occurrence of dry friction in the steering system. After formulating the requirements for the steering torque controller by specifying the target values for the characteristic parameters of the control device, a H_∞ type controller was developed which was implemented as a steering torque controller using frequency--dependent weighted functions.

2. Model of the EPS support device

Figure 1 shows an EPS device that has been removed from the vehicle and connected to the rack steering gear, and Fig. 2 shows the dynamic model of the system.

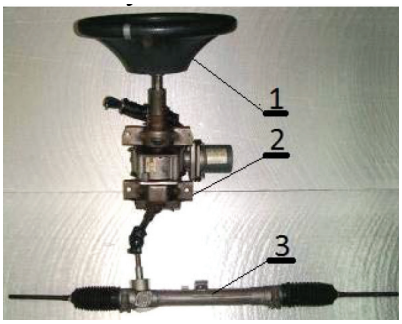

Fig. 1. The actual steering system with the electric assist device;
1 – steering wheel, 2 – EPS, 3 – steering gear

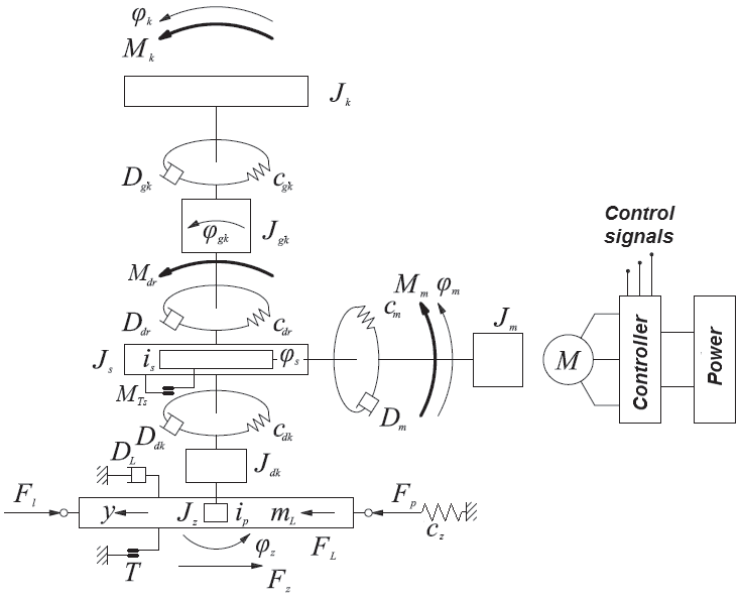

Fig. 2. The dynamic model of a steering system with electric assist device

Notation:

c_{dk} – angular stiffness of the lower part of the column
c_{dr} – angular stiffness of the torsion bar
c_{gk} – angular stiffness of the upper part of the column
c_{m} – angular stiffness of the electric motor clutch
c_{z} – stiffness of the elastic housing of the rack
D_{dk} – damping factor the lower part of the steering column
D_{dr} – damping factor of the torsion bar
D_{gk} – damping factor of the upper part of the steering column
D_{L} – damping factor of the rack
D_{m} – damping factor of the electric motor
F_{L} – external force of the steering rods imported from the axle rack
F_{l} – force in the left tie rod
F_{p} – force in the right tie rod
F_{z} – circumferential force on the pinion gear
i_{p} – steering gear ratio
i_{s} – worm gear ratio
J_{dk} – moment of inertia of the lower part of the column
J_{gk} – moment of inertia of the upper part of the column
J_{k} – moment of inertia of the steering wheel
J_{k+d} – moment of inertia of the steering wheel including mass of the hand
J_{m} – moment of inertia of the rotor of the electric motor
J_{s} – moment of inertia of the worm wheel
J_{z} – moment of inertia of the pinion
k_{e} – electromechanical constant
k_{ws} – constant assisted
M_{dr} – torque occurring on torsion rod
M_{k} – torque applied to the steering wheel
M_{m} – the electric motor torque assist device
M_{Ts} – friction torque of the worm gear
m_{L} – mass of the rack
T – friction force of the rack
y – shift of the rack
φ_{dk} – angle of rotation of the lower section of the steering column
φ_{gk} – angle of rotation of the upper part of the column
φ_{k} – angle of rotation of the steering wheel
φ_{m} – angle of rotation of the electric motor
φ_{s} – angle of rotation of the worm wheel
φ_{z} – angle of rotation of the pinion

The equations of the system dynamics shown in Fig. 2 are recorded as follows:

$$J_k\ddot{\varphi}_k + D_{gk}\left(\dot{\varphi}_k - \dot{\varphi}_{gk}\right) + c_{gk}\left(\varphi_k - \varphi_{gk}\right) = M_k \tag{1}$$

In view of the kinematic forced rotation of the steering wheel it was assumed that $\varphi_k = \varphi_{gk}$.

$$J_s\ddot{\varphi}_s + c_{dr}\left(\varphi_s - \varphi_k\right) + c_{dk}\left(\varphi_s - \varphi_z\right) + c_m i_s^2\left(\varphi_s - \frac{\varphi_m}{i_s}\right) = 0 \tag{2}$$

$$J_m\ddot{\varphi}_m + c_m\left(\varphi_m - \varphi_s i_s\right) + M_{Tm} = M_m \tag{3}$$

$$\left(J_{dk} + m_l r_z^2\right)\ddot{\varphi}_z + D_l r_z^2\dot{\varphi}_z + c_{dk}\left(\varphi_z - \varphi_s\right) + Tr_z + c_z r_z^2\varphi_z = \left(F_p + F_l\right)r_z \tag{4}$$

Damping of the rack described by the $D_l r_z^2\dot{\varphi}_z$ member was omitted. The engine torque depends on the stiffness and the angle of deflection of the torsion bar placed in series with the gear pinion described by constant k_{ws}:

$$M_m = k_{ws}c_{dr}\left(\varphi_k - \varphi_s\right) \tag{5}$$

Differential equations of motion of the booster are linear, thus it was possible to apply the principle of superposition. Therefore, differences in the variable waveforms with the power off and the variable waveforms corresponding to the system with the power on are caused by influence of unstable torque due to the introduction of additional torque of assist motor M_m. The numerical analysis results discussed later were verified experimentally on a specially built test bench.

The model of isolated steering system simulating the conditions of the bench measurements was formulated on the basis of the following assumptions:

- Sinusoidal kinematic input function caused changes of the angle φ_k of the steering wheel rotation with amplitude ±15° and frequency 0.5 Hz.
- External loading of the system is caused by the deformation of the spring elements having a coefficient of stiffness c_z connected in series with the gear rack.
- Assist torque from the electric motor is proportional (P-controller) to the torsional moment on the torsion bar mounted on the steering column.
- Friction forces are described using the model of Coulomb.
- Omitted from the model are:
- the impact of universal joints;
- flexibility of the rack gear housing;
- play in the moving joints;
- dynamics of the control system (sensors, transducers).

The mechanical model of the analysed system had three degrees of freedom: φ_k; φ_m; φ_z. Differential equations describing the dynamics of the system were solved in Matlab. As in [3], the torque of the EPS electric motor was treated as the product of the current i and the electromechanical constant k_e.

$$M_m = k_e \cdot i \tag{6}$$

Values of the parameters of the examined model are shown in Table 1.

Table 1. Values of the parameters of the tested EPS model

Values that were determined	Notation	Value	Unit of measure
moment of inertia of the steering wheel	J_k	$33 \cdot 10^{-3}$	kgm^2
moment of inertia of the upper part of the column	J_{gk}	$4.62 \cdot 10^{-5}$	kgm^2
moment of inertia of the worm wheel	J_s	$0.83 \cdot 10^{-3}$	kgm^2
moment of inertia of the rotor of the electric motor	J_m	$0.0321 \cdot 10^{-3}$	kgm^2
moment of inertia of the lower part of the column	J_{dk}	$0.002 \cdot 10^{-3}$	kgm^2
moment of inertia of the pinion	J_z	$5.48 \cdot 10^{-6}$	kgm^2
angular stiffness of the upper part of the column	c_{gk}	9800	Nm/rad
angular stiffness of the torsion bar	c_{dr}	91	Nm/rad
angular stiffness of the electric motor clutch	c_m	3.85	Nm/rad
angular stiffness of the lower part of the column	c_{dk}	2400	Nm/rad
stiffness of the elastic housing of the rack	c_z	$1.7 \cdot 10^6$	N/m
damping factor of the upper part of the steering column	D_{gk}	0.0275	Nms/rad
damping factor of the torsion bar	D_{dr}	0	
damping factor of the electric motor	D_m	0.0035	Nms/rad
damping factor the lower part of the steering column	D_{dk}	0	
damping factor of the rack	D_L	0.0275	Ns/m
worm gear ratio	i_s	0.0455	
steering gear ratio	i_p	20.5	rad/m
mass of the rack	m_L	1.45	kg
friction force of the rack	T	175	N

3. Workplace tests

A steering system with a rack gear and an EPS supporting device was installed on a special measurement and research stand (Fig. 3). The advantage of this is stand is that it was created from the deconstruction of this part of the CAN communication, which is essential in cars for the operation of steering assistance. The amount of assistance was dependent upon the set driving speed. Two types of steering rotation were generated.

In the first type of steering rotation (test I), a direct-current (DC) motor with two different rotational speeds was used to drive the steering wheel, allowing a steady rotation

of the steering wheel. The input torque was transferred to the steering column via a worm gear and a toothed belt. This enabled testing at two rotational speeds of the steering wheel: 0.2 rpm and 0.4 rpm. The drive system of the steering wheel was equipped with circuit breakers in order to protect against overload resulting from the extreme positions of the rack. These breakers allowed the reversible operation of the stand with steering wheel rotation in the range of ±500°.

In the second type of extortion (test II), harmonic kinematic exclusion was first performed from the steering wheel side and then from the rack side using a connecting rod machine originally used to determine the characteristics of the shock absorbers. This machine was powered by a 40 kW DC motor. Variable stroke adjustment in the range of 0–100 mm and smooth regulation of the frequency of excitation were possible. The uniformity of the drive was ensured by the flywheel with an inertia moment of 17.0 kgm^2.

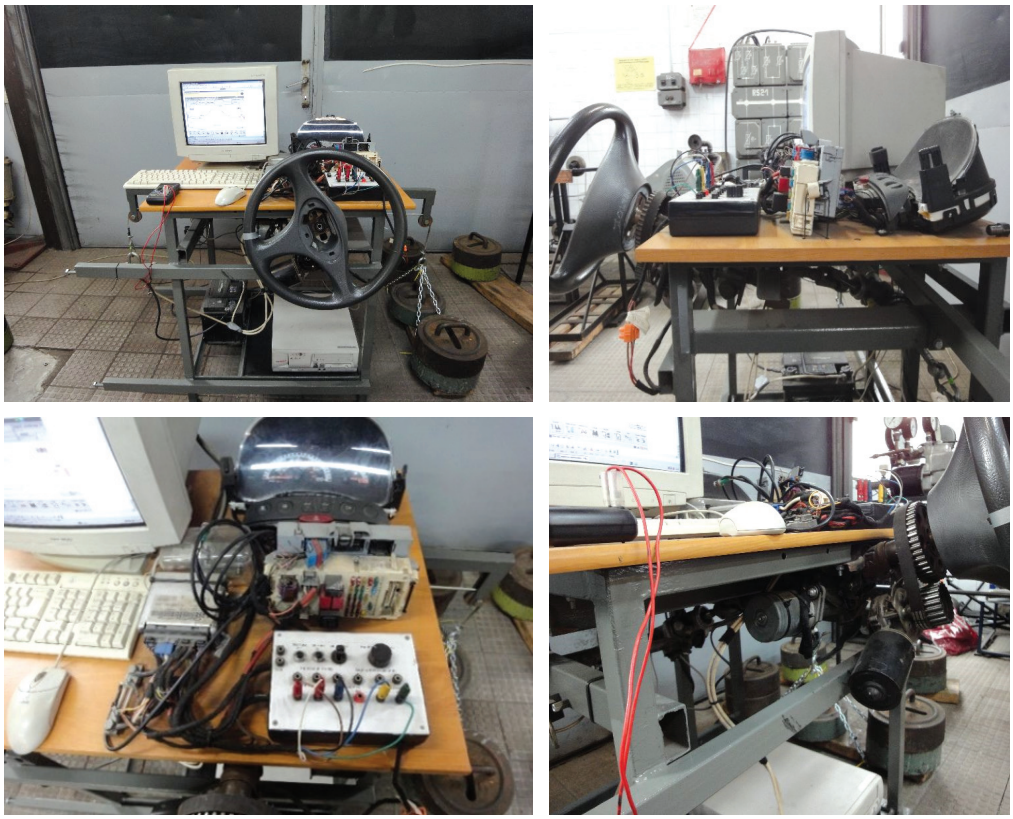

Fig. 3. View of the test bench for the EPS device with equipment

Measurements of forces and displacements were performed by equipping the stand with additional external devices, specifically, HBM force sensors and wire sensors to measure displacements (turn of the steering wheel, shift of the rack).

Table 2. Listing of external measuring equipment

Sensor type	Type	Measurement range	Accuracy
force sensor	HBM U2B	20 kN	±0.02%
position sensor	Kubler DB3A1	500 mm	±0.1%

For the driver's input function, the steering wheel was connected to the machine connecting rod fastener using a 1.5-m-long connector with ball joints. The wire sensors were used to measure the angle of rotation of the steering wheel and the displacement of the toothed bar. The cable for measuring the angle of the rotation of the steering wheel was wound on a wheel mounted on the steering column shaft, which was coaxial with the steering wheel.

At the input function from the side of the steering wheel, the load on the rack was obtained by elastic elements of a stiffness, connecting the gear rack to the housing.

3.1. Tests of the input function of the steering wheel

Two types of tests were performed on the input function of the steering wheel:

- rotation of the steering wheel by an angle of ±500°,
- harmonic excitation in the range of ±15°.

During tests with a steering wheel rotation of ±500°, the transmission worked without a load and the steering wheel rotation was at one of two values: either the speed of around 0.2 rpm or 0.4 rpm.

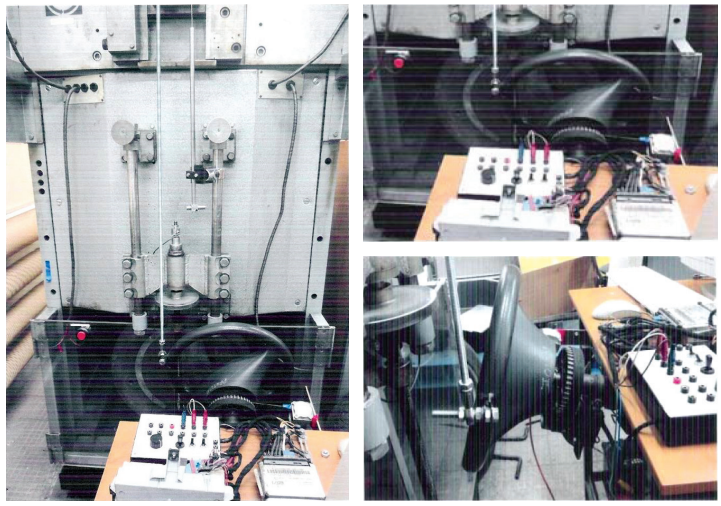

Fig. 4. Bench tests with harmonic input function from the steering wheel in the range of ±15°

Taking into account the transmission ratio of the rack gear, the harmonic input function of the steering wheel caused the displacement of the rack by approx. 2.5 mm. The investigations concerned two cases: a free (unloaded) rack; a rack supported by elastic elements with a stiffness of around $1.7 \cdot 10^6$ N/m.

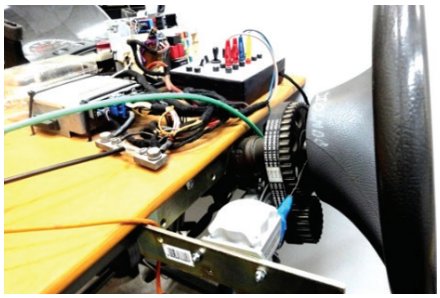

Fig. 5. Work bench tests with kinematic input function on the steering wheel side within the range of ±500° rotation

The bench tests included measurements of the torque at a ±15° steering wheel rotation in which the movements of the steering wheel are performed during the correction that takes place during the process of driving.

In order to determine the torque developed by the motor M_m at different booster operating states, the characteristics $M_k = {}_f(\varphi_k)$ were first determined with the booster switched off, followed by the same input parameters (amplitude $\varphi = \pm 15°$ and frequencies f = 0.5, 1.0, 1.5 Hz) with the assistive device switched on.

The constructed test stand proved to be sufficiently functional and the registered characteristic curves showed repeatability.

3.2. Tests at the input function from the rack

The tests of the steering system at the kinematic input function of the gear rack movement were performed on the modernised stand (Fig. 6).

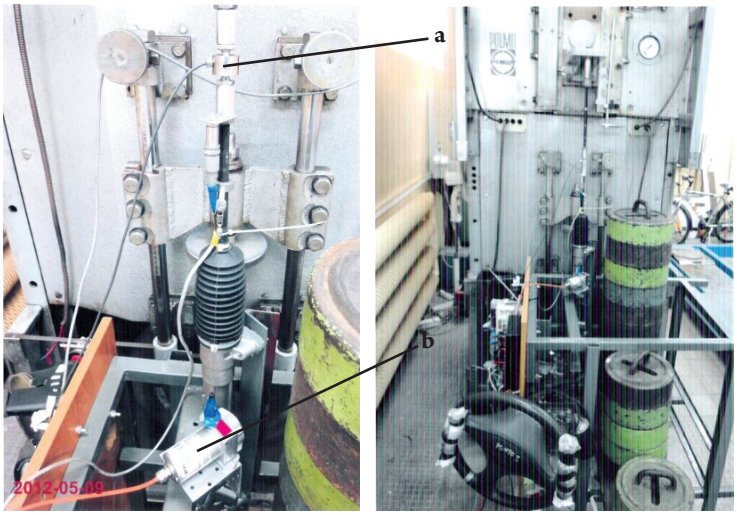

Fig. 6. Research on kinematic input function from the rack mounted in a vertical position; a – force sensor, b – position sensor

The adaptation of the stand consisted of the articulated connection of the gear rack with the machine slider for, among other purposes, testing the shock absorbers using the steering rod (with factory ball joints) on which the force sensor was mounted. The amplitude of the input function had a fixed value of ±15 mm. Such a displacement of the rack caused rotation of the steering wheel in the range of approximately ±175°. The frequency of the input function excitation was either 0.1 or 1.0 Hz.

The tests concerned transmission with an assistance mounted with different loading of the system: free steering wheel without additional weight; steering wheel loaded on the circumference with weight 0.8 kg multiplied by 2, replacing the weight of the driver hand and forearms placed freely on the steering wheel.

A very strong dependence of the dynamic load of the rack on the size of additional masses attached to the steering wheel was observed. In the case of the steering wheel without additional weight, the force in the rack did not exceed 0.75 kN. There were noticeable vibrations related to the torsional elasticity of the torsion bar. With mounted masses of 0.8 kg multiplied by 2, and a similar kinematic input function – the force loading the sprocket increased around four times up to nearly 3 kN.

3.3. Comparison of the results of bench and simulation tests

Two simulation tests were performed.

Test I referred to forcing the rotary-oscillating motion of the steering wheel with a sinusoidal waveform and is described by the following parameters: frequency of input function 0.5 Hz, the absence of a load on the side of the rack ($c_z = 0$), and simulated car speed of 0 km/h. Figure 7 shows the time courses of changing the angle of rotation of the steering

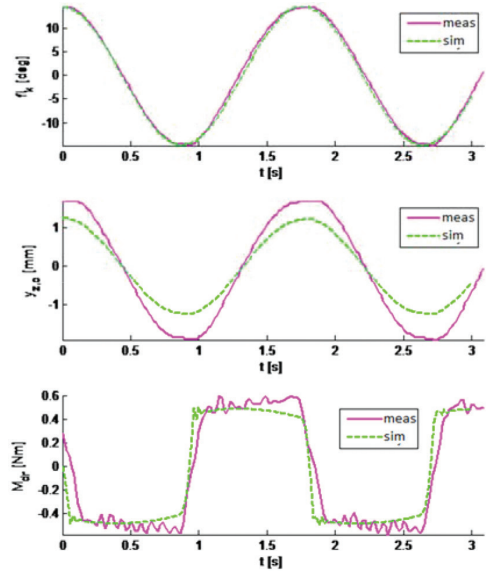

Fig. 7. Comparison of time courses from bench measurements and simulations during Test I

wheel φ_k and the displacement of the rack relative to the housing $y_{z,o}$. Figure 8 presents the torque courses of the torsion bar M_{dr} equal to the torque at the steering wheel M_k.

When forcing a change in the angle φ_k with a sinusoidal pattern, the occurring displacement of the rack $y_{z,0}$ is similar and only slightly changed by the friction forces at the extreme positions. A smaller displacement of the $y_{z,o}$ racks was obtained with the model in comparison with the bench tests. The mapping of moment changes of the M_{dr} torsion bar is satisfactory with regard to the phase and amplitude of the response, although according to the model, the changes do not show vibrations at the vertices of the waveform. The above statements are also confirmed by the torque characteristics as a function of the angle of rotation of the steering wheel, which is shown in Fig. 8.

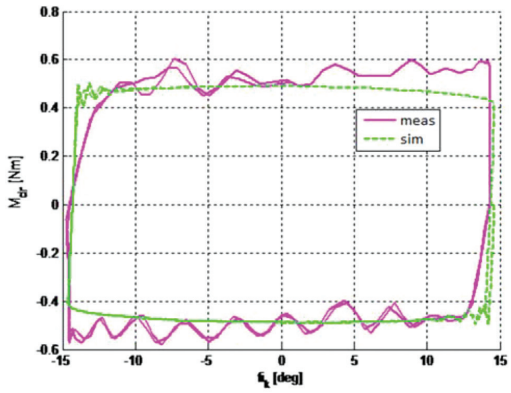

Fig. 8. Comparison of example runs from bench measurements and simulations of torque changes on the steering wheel $(M_{dr} = M_k)$ as a function of the angle of rotation of the steering wheel

Test II consisted of forcing a rotational-oscillating motion of the steering wheel with a sinusoidal waveform, where the frequency of input function is 0.5 Hz, loads on the side of the rack with stiffness $c_z = 1.7 \cdot 10^6$ N/m, and the simulated car speed = 0 km/h. Figure 9 shows the changes of the steering wheel rotation angle φ_k, the displacement of the rack with respect to the housing, $y_{z,o}$ and the moment of the M_{dr} torque rod equal to the torque at the M_k steering wheel.

Due to an applied sinusoidal input function, φ_k moves along a similar course as $y_{z,o}$, which is slightly deformed by friction forces in extreme positions. In the model's response, a smaller amplitude of displacement of the $y_{z,o}$ racks was obtained. The mapping of torque changes on the M_{dr} torsion bar is satisfactory with regard to the phase and amplitude of the response, although the variables determined through the use of the model do not show interference at extreme positions.

Details of the results obtained from the model in the form of a torque graph as a function of the angle of rotation of the steering wheel are shown in Fig. 10.

The waveforms of the variables determined by the model are satisfactorily represented in relation to the hysteresis loop width and the average slope of the characteristic, although this is not very similar to the S-letter profile. The linear course without accentuating the S-letter

profile can be explained by the linear dependence of the torque of the auxiliary motor from the steering angle of the control rod with the torque value assumed in the model. In fact, as research shows, the dependence is not linear and it is progressive.

The adopted simulation model of the electrical booster satisfactorily describes the real object despite the introduced simplifications. There is a noticeable influence of friction, which causes a hysteresis loop effect with a width similar to the previously measured one. The vibrations, which are small but noticeable at higher frequencies in the study, are not true to a simulative mapping. It could be caused by the irregular torque of the DC motor.

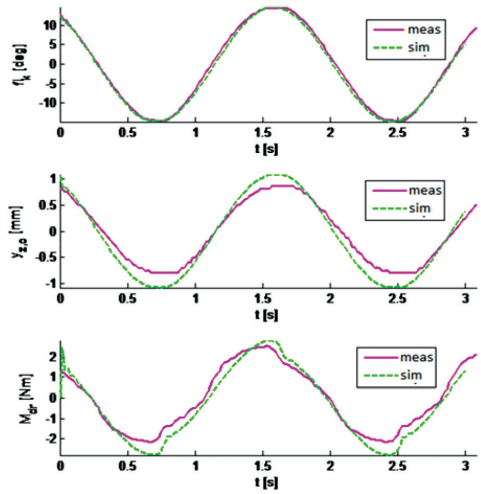

Fig. 9. Comparison of time courses from bench measurements and simulations during Test II

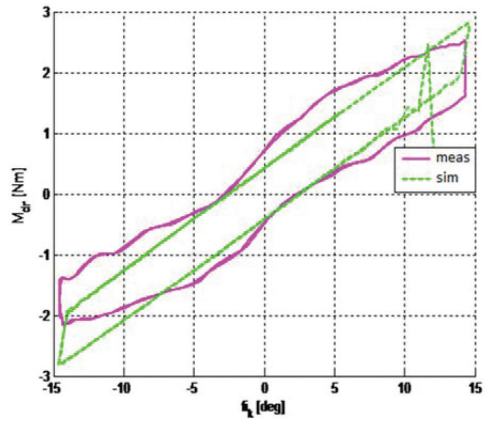

Fig. 10. Comparison of example runs from bench measurements and simulations of torque changes on the steering wheel ($M_{dr} = M_k$) as a function of the angle of rotation of the steering wheel

It can be assumed that a better representation of the actual characteristics of the transmission can be obtained if instead of the linear relationship between the torque of the motor and the load of the transmission, the non-linear function is introduced.

The EPS current characteristics were determined on the same bench. The waveform of changes in current values as a function of the torque on the steering wheel at different speeds is shown in Fig. 11. It was found that the value of EPS current as a function of the torque for an assumed velocity increases to a certain value in a non-linear manner, and after reaching the value imposed by the limiter, it is intentionally limited and takes an almost constant value.

The equation approximating a non-linear increase in the current can be written as:

$$I(M) = a \cdot M \cdot e^{b \cdot M} \tag{7}$$

where a, b, and e are parameters dependent upon speed.

Estimation of parameters a and b by the method of least squares at a confidence level of 95% enabled determining the function approximating the results of measurements in a range of non-linear dependence. Based on the measurements, it was assumed that in the range of linear dependence, the current is constant.

$$I(M) = const = c \tag{8}$$

Theoretical characteristics (Fig. 12) of the current intensity obtained at different speeds were similar to obtained results of the measurements (Fig. 11). Appropriate values of the parameters a, b and c were determined. The values of these parameters at speeds within the range of 0–160 km/h with increments of 20 km/h are shown in Table 3.

Table 3. Values of the parameters of the equation (8) describing the EPS current

v km/h	a	b	c
0	0.74	0.33	37.5
20	0.24	0.43	22.5
40	0.24	0.31	17.5
60	0.16	0.30	14.8
80	0.07	0.38	14.6
100	0.11	0.31	14.8
120	0.10	0.33	15.0
140	0.09	0.34	15.0
160	0.09	0.33	15.0

Figure 11 shows changes in the intensity of the current supplying EPS as a function of the torque on the steering wheel. Changes in the intensity of the EPS current as a function of the steering wheel torque when simulated at different driving speeds are shown in Fig. 12. On account of ensuring legibility of the drawing, the number of speeds plotted was limited to only six. Figure 13 shows changes in the intensity of the EPS supply current when the vehicle is at a standstill.

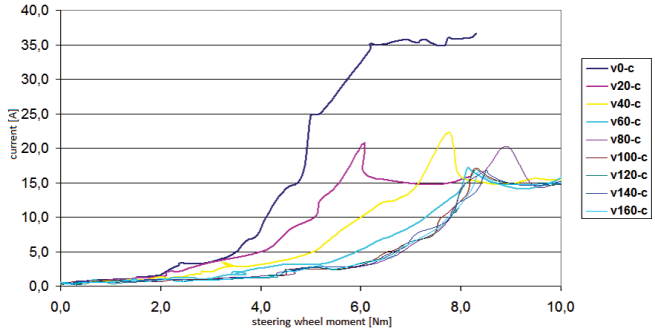

Fig. 11. Chart of assist-motor current intensity depending upon the steering wheel torque

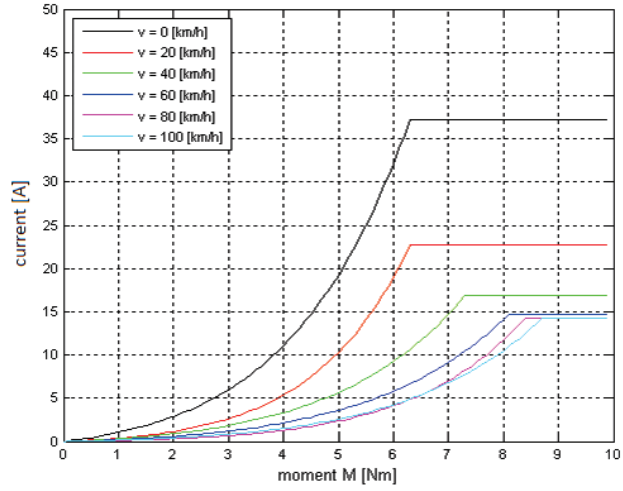

Fig. 12. Changes in EPS current intensity as a function of the torque on the steering wheel different speeds simulated on the bench

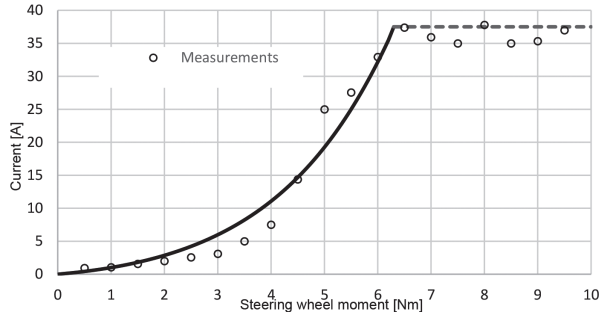

Fig. 13. Changes in current intensity as a function of the torque on the steering wheel; velocity $v = 0$ km/h

The method of controlling the current intensity as a function of the steering wheel torque and dependent upon the driving speed is shown in the spatial diagram (Fig. 14).

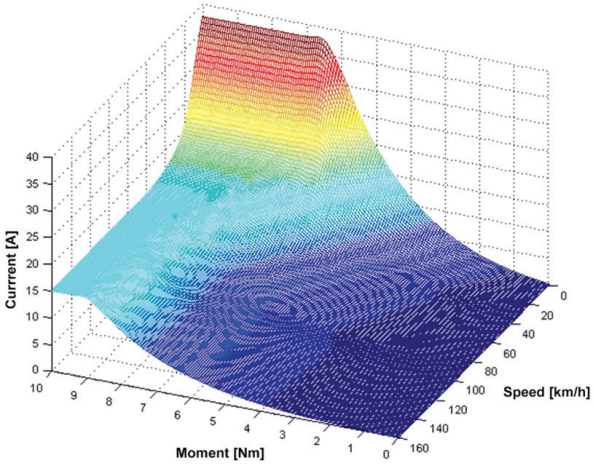

Fig. 14. Changes in EPS current intensity as a function of the torque on the steering wheel and variable speed

The torque developed by the engine of the booster is dependent upon the current value of the electromechanical constant, hence the fact that the shape of the shell $I = f(M_k)$ maps the shape of the support characteristic. The current intensity value is the resultant value of the EPS device controller and it determines the course of the characteristics.

4. Conclusions

Waveforms determined by the model are satisfactorily well represented in relation to the width of the hysteresis loop and the average slope of the characteristic (Fig. 10), again this seems very vague – you should clearly state which characteristic you are referring to although this does not demonstrate a clear similarity with the S-profile. The linear course without emphasising the S-profile can be explained by the linear dependence of the torque between the auxiliary motor and the steering angle controlling the torque value in the model. In fact, as this research shows, the dependence is not linear; it has a progressive character.

The adopted simulation model of the electrical booster, despite the introduced simplifications, satisfactorily describes the real object. There is a noticeable influence of friction, which causes a hysteresis effect with a width similar to the previously measured one. The vibrations, which are small but noticeable at higher frequencies in the study, are not true to a simulative mapping.

It can be assumed that a better mapping of the actual transmission characteristics can be obtained if instead of the linear relationship between the engine torque and the transmission load, a non-linear function is introduced.

The author is also an employee of the Institute of Forensic Research (Instytut Ekspertyz Sądowych im. prof. dra Jana Sehna).

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The application of failure mode and effects analysis (FMEA) for the risk assessment of changes in the maintenance system of railway vehicles

Zastosowanie analizy przyczyn i skutków uszkodzeń (FMEA) do oceny ryzyka zmian w systemie utrzymania kolejowych środków transportu

Abstract

This paper presents the application of failure mode and effects analysis (FMEA) for the risk assessment of changes in the maintenance system of railway vehicles based on the example of the 6Dg type shunting locomotive. The application example is preceded with an introduction to the methodological basis of FMEA, which is specified in literature and standards. In order to ensure the comparability of the analysis results with vehicles of a similar type and to quantify the risk components (the probability of hazard occurrence, the consequences of the occurrence of a hazard and the possibilities of hazard detection) the classification which applies to shunting locomotives was used. Based on the conducted analysis, the possibility to make changes to the maintenance plan for 6Dg locomotives which would not be in breach of the acceptable safety level was demonstrated and preventive safety measures were determined.

Keywords: railway systems, maintenance systems, risk assessment, FMEA

Streszczenie

W pracy przedstawiono zastosowanie analizy przyczyn i skutków uszkodzeń (FMEA) do oceny ryzyka zmian w systemie utrzymania kolejowych środków transportu na przykładzie lokomotywy manewrowej typu 6Dg. Przykład aplikacyjny poprzedzono wprowadzeniem do podstaw metodycznych analiz FMEA, które są precyzowane w licznej literaturze i normach. W celu zapewnienia porównywalności wyników analizy z pojazdami podobnego typu do kwantyfikacji składowych ryzyka: prawdopodobieństwa wystąpienia zagrożenia, skutków zagrożenia i możliwości wykrycia zagrożenia, zastosowano klasyfikację odnoszącą się do lokomotyw manewrowych. Na podstawie przeprowadzonej analizy wykazano możliwość wprowadzenia zmian w planie utrzymania lokomotyw, jak również określono prewencyjne środki bezpieczeństwa.

Słowa kluczowe: systemy kolejowe, systemy utrzymania, ocena ryzyka, analiza FMEA

Abbreviations

ALARP – as low as reasonably practicable
CSM – common safety method
ETA – event tree analysis
FMEA – failure mode and effects analysis
FMECA – failure mode, effects and criticality analysis
FTA – fault tree analysis
HAZOP – hazard and operability study
MDBHF – mean distance between hazardous failures (km)
MSD – maintenance system documentation
MTBHF – mean time between hazardous failures (hr)
PHA – preliminary hazard analysis
RAMS – reliability, availability, maintainability, safety
RPN – risk priority number (-)
VSC – vehicle safety controls

Symbols

c – the size of losses caused by a hazardous event (-)
D – parameter of the potential of hazard identification (-)
H – frequency of hazardous failures (failure/hr or failure/km)
k – cause of hazard (-)
$r_1(z_k)$ – risk component corresponding to the criterion of the probability of hazard occurrence 'O' (-)
$r_2(z_k)$ – risk component corresponding to the criterion of the consequences of the occurrence of a hazard 'S' (-)
$r_3(z_k)$ – risk component corresponding to the criterion of the possibilities of hazard detection 'D' (-)
O – frequency of the occurrence of hazard (-)
S – scale of losses involved in the occurrence of hazard (-)

1. Introduction

The prevailing formal document for the assessment of safety in rail transport is Directive 2004/49/EC of the European Parliament and the Council of 29 April 2004 on safety on the Community's railways. The currently applicable version was amended by Directive 2008/110/EC of the European Parliament and the Council of 16 December 2008 and Commission Directive 2014/88/EU of 9 July 2014. The principles for the common safety method (CSM) concerning the risk analysis are described in Commission Implementing Regulation (EU) No. 402/2013 [2].

A detailed algorithm for the process of risk management is presented in the appendix to the aforementioned regulation entitled *Risk management process and independent assessment*. The procedure of risk qualification in the case of technical, operational or organisational changes in rail transport requires an analysis of the significance of the proposed changes. The procedure is not required to be applied where the proposed change does not have an effect on the safety of the railway system or if, after the application of the criteria specified in Article 4(2) of the appendix, it is certain that the risk involved therein falls within the permitted level. If there is no such certainty, the change should be subjected to the risk qualification procedure [13].

The aim of the risk qualification is to demonstrate the conformity of the change with the safety requirements. To begin, the system needs to be defined with regard to its scope, functions and interfaces, which is then followed by a risk analysis comprising the identification and classification of hazards and the choice and application of the risk acceptance principle. This forms the basis for performing risk analysis and identifying the relevant safety requirements or measures to be implemented as the ultimate effect of the risk qualification process.

If it is demonstrated during the identification and classification of the hazards that the risk concerning the changes under analysis is essentially permitted, then the process which has been commenced is stopped and the decision taken need only be substantiated and documented; if this is not the case, the process is continued. In accordance with the regulation, at least one of three risk acceptance methods needs to be chosen; these are as follows:

- application of the codes of practice,
- application of a reference system,
- explicit risk estimation.

The last principle requires the choice of specific safety criteria; these may be either qualitative or quantitative. The quantitative criteria are defined in the regulation and include estimated frequency of 'accidents and incidents resulting in harm caused by a hazard' and the estimated 'degree of severity of the harm'. Appendix E of the standard PKN-CLC/TR 50126--218 [9] presents a comparison of a dozen or so methods of estimating the explicit risk used in analysing railway systems, including rail vehicles; these methods are as follows:

- FMEA (failure mode and effects analysis);
- HAZOP (hazard and operability study);
- PHA (preliminary hazard analysis);
- FTA (fault tree analysis);
- ETA (event tree analysis);
- matrix method;
- index-based method (e.g. risk score), and others.

Depending on the acceptance principle which has been adopted, it should be decided at the risk assessment stage whether the risk that is analysed is permissible compared with the existing criteria. The standards for the assessment of safety in railway systems [3–5, 9–11] present general guidance which enables a reduction of the occurrence of hazards to the minimum acceptable level in accordance with the ALARP (as low as reasonably practicable) principle which is based on the division of risk into the following three areas:

1. upper limit where it is mandatory to take up measures to reduce the risk;
2. tolerable risk (so-called ALARP) area where appropriate remedial measures and risk control measures should be undertaken;
3. lower risk limit where the risk level is acceptable and further measures are not required.

The distinctions between acceptable, tolerable and non-acceptable risks are set by acts of law on railways (directives, regulations, standards, internal procedures of the safety management system of railway carriers) – these are blurred dividing lines which, in qualitative terms, relate to applicable requirements set for objects. If a vehicle meets these requirements, it is considered safe for humans and for the environment. This paper presents a method of estimating explicit risk through the application of FMEA (failure mode and effects analysis), which is amongst those methods most frequently applied by Polish railway carriers.

2. Methodological basis of failure mode and effects analysis

As stated in the introduction, FMEA is one of many methods of explicit risk estimation. The aim of FMEA is to assess the risk involved in the occurrence of hazards and undertake measures to control or eliminate it, primarily with regard to hazards relevant for the railway system. The FMEA method with reference to various technical systems and facilities is widely described in literature [1, 7, 8, 11, 12, 14–18] and standards, for example:

- MIL-STD-1629A Procedures for Performing a Failure Mode, Effects and Criticality Analysis;
- BSI BS 5760-5:1991 Reliability of systems, equipment and components – guide to failure modes, effects and criticality analysis (FMEA and FMECA), IMO MSC Resolution 36(63) Annex 4 – Procedures for Failure Mode and Effects Analysis;
- PN-EN 60812 Failure modes and effects analysis (FMEA and FMECA).

The procedure for performing FMEA for rail vehicles is presented in Fig. 1.

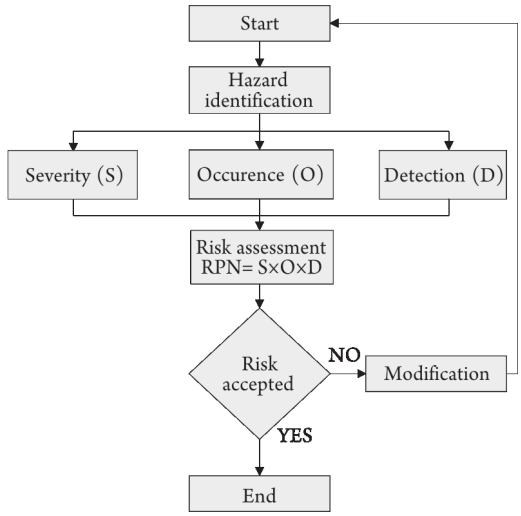

Fig. 1. Procedure for implementing FMEA for a rail vehicle

3. Application of the FMEA method for risk qualification

As an application example of FMEA for risk qualification, changes in the maintenance system of 6Dg diesel locomotives (Fig. 2) is presented. FMEA is required by the procedure *Identification of hazards and risk assessment of the Safety Management System* of the railway carrier operating the locomotives.

Fig. 2. View of 6Dg type diesel locomotive

4. Risk of hazard occurrence

FMEA is a quantitative method in which the risk of occurrence of any identified type of hazard is expressed using the RPN (risk priority number). According to the standard EN 60812:2018 *Failure modes and effects analysis* (*FMEA and FMEC*A), the RPN may be obtained using the following expression [6]:

$$\mathrm{RPN}(z_k) = \prod_{i=1}^{3} r_i(z_k) \Rightarrow \mathrm{RPN} = O_k \cdot S_k \cdot D_k \tag{1}$$

where:

$r_1(z_k)$ – risk component corresponding to the criterion of the probability of hazard occurrence 'O',

$r_2(z_k)$ – risk component corresponding to the criterion of the consequences of the occurrence of a hazard 'S',

$r_3(z_k)$ – risk component corresponding to the criterion of the possibilities of hazard detection 'D',

k – cause of hazard.

The above elements are assessed on a scale of 1 to 10 based on the classification criteria which were adopted. The risk assessment ratio RPN takes values from between 1 and 1000. Various techniques for categorising risk components are proposed in standards and literature. The number of categories, their scale and description should match the particular object of study in order to ensure the comparability with vehicles of a similar type operating in similar conditions. In the case of a 6Dg locomotive, the divisions which apply to shunting locomotives are used to quantify the frequency of the occurrence of hazard O (Table 1).

Table 1. Categories of the probability of hazard occurrence

Ratio 'O'	Frequency of occurrence of the hazard H		Qualitative classification	Description of the probability of occurrence
	[failure / hr operation]	[failure / km]		
1–2	$H \leq 10^{-6}$	$H \leq 10^{-7}$	unlikely	The probability of the occurrence of a hazard is marginal and will likely not occur.
3–4	$10^{-6} < H \leq 10^{-5}$	$10^{-7} < H \leq 10^{-6}$	rather unlikely	The probability of the occurrence of a hazard is low. The causes of the hazard are very rare.
5–6	$10^{-5} < H \leq 10^{-4}$	$10^{-6} < H \leq 10^{-5}$	occasional	The probability of hazard occurrence is medium. The causes of the hazard occur occasionally.
7–8	$10^{-4} < H \leq 10^{-3}$	$10^{-5} < H \leq 10^{-4}$	likely	The probability of hazard occurrence is high. The causes of the hazard occur frequently.
9–10	$H > 10^{-3}$	$H > 10^{-4}$	frequent	The probability of hazard occurrence is very high. It is nearly certain that the hazard will occur.

The scale of losses involved in the occurrence of hazard S was referred to human losses estimated by means of the equivalent fatalities and financial losses. The classifications of the consequences of the occurrence of a hazard are presented in Table 2.

Table 2. Categories of the consequences of the occurrence of a hazard

Ratio 'S'	Human losses (equivalent fatality)	Financial losses (euro)	Qualitative classification	Description of the effects of the occurrence of hazard
1	none	none	negligible	The effects of the hazard are irrelevant for the safety level.
2–3	one slightly injured person ($0 < c \leq 0.01$)	between 0 and 50,000	low	The effects of the hazard may be small and may only cause a minor reduction in the safety level (disruptions in railway transport, delays).
4–6	several slightly injured persons ($0.01 < c \leq 0.1$)	between 50,000 and 0.5 million	significant	The effects of the hazard may be quite considerable and cause a reduction in the safety level (incident, slightly injured persons).
7–8	many severely injured persons or one fatality ($0.1 < c \leq 1$)	between 0.5 million and 2 million	serious	The effects of the hazard may be serious and cause a considerable reduction in the safety level (railway accident, seriously injured persons, fatality).
9–10	many fatalities ($c > 1$)	more than 2 million	catastrophic	The effects of the hazard may be very serious and lead to a dramatic reduction in the safety level (serious railway accident, fatalities).

The parameter of the potential of identification of hazard *D* defines the possibility of diagnosing a potential hazard (Table 3). The inclusion of this characteristic makes FMEA different from other risk acceptance methods. The possibility of earlier hazard detection by advanced systems of on-board diagnostics or the application of advanced tools and methods of tests during checks or maintenance has a material effect on the ensuring of a high level of safety in the operation of the vehicle.

Table 3. Categories of the possibilities of hazard detection

Ratio 'D'	Qualitative classification	Description of hazard detection possibilities
1–2	very high	The probability of hazard detection is very high. Identification of the cause of the error is certain.
3–4	high	The probability of hazard detection is high. The control measures which are applied enable the identification of the cause of the error. Symptoms for the occurrence of the cause are noticeable.
5–6	average	There is an average probability of hazard detection. The control measures may enable the identification of the cause of the error. Symptoms may be established and identified which indicate the possibility of hazard occurrence.
7–8	low	There is a low probability of hazard detection. It is very likely that the control measures which are applied will not make it possible to identify the cause of the error. It is very difficult to identify the cause of the error.
9–10	very low	Minimal probability of hazard detection. It is practically impossible to identify the cause of the error.

In accordance with the guidelines for the procedure of the identification of hazards and the technical risk assessment applied by the carrier, the FMEA method identifies three risk levels on the basis of the so-called risk matrix (Table 4). Depending on the calculated RPN, an assessment is performed of which hazards involve the highest risk. Hazards with an RPN figure higher than 120 are relevant. The higher the RPN figure, the more relevant the hazard for the railway system. RPN figures above 150 relate to events which pose a direct threat to the safety of the railway system. Where the risk *R* is in class 3, process control measures should be undertaken to eliminate the hazard or limit its effects. Preventive, corrective measures should be addressed in the first instance to items with a high RPN figure.

Table 4. Risk levels applied in the FMEA according to the procedure applied by the carrier

Risk class	RPN	Risk level	Description
1	RPN ≤ 120	acceptable	Measures to eliminate the hazard are not required to be taken.
2	120 < RPN ≤ 150	tolerable (ALARP level)	Means and/or measures eliminating the hazard and reducing risk should be identified.
3	RPN > 150	unacceptable	This is a hazard which poses a direct threat to the railway system safety.

5. Risk estimation sheet

Table 5 presents the mean times to failure and mean times between hazardous failures for selected systems and elements of a 6Dg locomotive having an impact on the safety of railway transport.

Table 5. Mean time to failure and time between hazardous failures for selected systems and elements

No.	Description	MTBHF [hr]	MDBHF [km]
1.	**Running gear**	**27,506.3**	**178,200.0**
1.1.	failures and wear of the wheels' outer contour	27,506.3	178,200.0
2.	**Brake system (pneumatic and mechanical parts)**	**6,430.0**	**41,657.1**
2.1.	failures of the main or auxiliary compressor	18,337.5	118,800.0
2.2.	failures of the engine driving the main or auxiliary compressor of rail vehicle	165,037.5	1,069,200.0
2.3.	failures of pneumatic valves (inter alia, main or auxiliary valve of the driver, reducing valve, end valve, safety valve)	29,124.3	188,682.4
2.4.	failures of pneumatic conduits	41,259.4	267,300.0
2.5.	failures of the actuator in the brake system	247556.3	1,603,800.0
2.6.	failures of other elements in the pneumatic circuit	49,511.3	320,760.0
2.7.	failures of elements of the brake, e.g. levers, couplers, coupling pins, bushings, couplings, brake blocks	82,518.8	534,600.0
3.	**Train drive safety control engineering devices**	**8,841.3**	**57,278.6**
3.1.	failures of vehicle safety controls (VSC), metering device (speed meter, ammeter) or radiotelephone	8,841.3	57,278.6

Based on the above-calculated figures and the aforementioned assessment criteria, Table 6 presents a FMEA sheet with the results of the estimated risk for the identified hazards relevant for the safety of the railway transport of a 6Dg locomotive.

6. Analysis of the results and preventive safety measures

The analysis demonstrated that the highest frequencies of the occurrence of threats (parameter O) relate to failures of the vehicle movement safety controls. Detailed identification of the recorded occurrences showed that the measuring devices and the radiotelephone are the weakest elements in this structural group.

The highest figures of losses involved in the occurrence of a threat (parameter S) and the highest chances for detecting the threat (parameter D) were estimated for the threats which are not currently present and which link to the possibility of fatigue-related cracks in the structural nodes of the vehicle frame (support) and the bogie support. Analysis of the results demonstrated that the permitted risk level of RPN ≤ 120 was not exceeded for any of the hazards. The highest risk of hazard was noted for failures of the automated vehicle safety controls, checking apparatus or radiotelephone $RPN_9 = 70$ ($O = 7$, $S = 5$, $D = 2$).

Table 6. Risk estimation sheet using the FMEA method for a 6Dg locomotive

No.	Hazard	Potential consequences	Existing inspection methods	O	S	D	RPN	Additional control methods
1	2	3	4	5	6	7	8	9
Running gear								
1.	failure of or wear of the wheels' outer contour	increase in dynamic loads, exceeding the permitted wear, wheel thread failure, cracking of the rim, derailing of locomotive	check and parametric cards in the MSD of wheel sets and wear check cards of the rims of wheel sets manual for the checking and technical assessment of wheel sets of rail vehicles Ct-4	5	2	2	**20**	introduction within P3 level of flaw-detection tests of wheel sets
Brake system (pneumatic and mechanical parts)								
2.	failure of the actuator in the brake system	slower response of the brake system, elongation of the braking path, incapacity to drive	check and parametric cards in the MSD of the brake and pneumatic system check cards and protocols in the MSD of the brake – mechanical part manual for the operation and maintenance of brakes in railway rolling stock Cw1	3	3	1	**9**	not required
3.	failure of elements of the brake	failure of brake gear, jamming of the wheel set, heating of the wheel rim, incapacity to drive		5	3	3	**45**	not required
4.	failure of main or auxiliary compressor	no air in the brake system, vehicle immobilisation	check the technical condition in accordance with the compressor's technical requirements for the production and acceptance; check cards in the MSD of the compressor unit	6	2	1	**12**	not required
5.	failure of the engine driving the main or auxiliary compressor of rail vehicle	problem with controlling the vehicle's brake	check cards in the MSD of the pneumatic system	4	3	1	**12**	not required
1	2	3	4	5	6	7	8	9

6.	failure of pneumatic valves	unstable operating parameters of the pneumatic system, possibility of excessive pressure growth	check cards in the MSD pneumatic system	5	2	2	**20**	not required
7.	failure of pneumatic conduits	drop in air pressure, automatic vehicle braking, intensive work of the compressor	check cards in the MSD of the pneumatic system	5	2	3	**30**	not required
8.	failure of other elements in the pneumatic conduit	drop in air pressure, no possibility to switch the system down, incapacity to drive	check cards in the MSD of the pneumatic system	5	2	2	**20**	not required
	Vehicle safety control devices							
9.	failure of the vehicle safety controls (VSC), metering device or radiotelephone	no signal and reception, disruptions in communications, vehicle's incapacity to drive, collision or derailing of the locomotive	check cards and protocols in the MSD of the metering systems, brake automation system, dead man's switch and Radio Stop	7	5	2	**70**	not required
	Vehicle support structure							
10.	corrosion wear of the bogie support or frame	decommissioning in the event of exceeding corrosion of 0.2 mm of the thickness of sheet metal of the support or 0.2 of the thickness of sheet metal of longerons, headstocks and transverse colon	check cards and protocols in the MSD of the bogie support and frame rail vehicle maintenance manual Ct-3	1	5	4	**20**	not required
11.	cracks in the support's nodes	damage of the construction structure, propagation of fatigue cracking in further operation	check and parametric cards in the support's MSD rail vehicle maintenance manual Ct-3	1	6	4	**24**	visual assessment of the condition of the nodes of the support at the P2 maintenance level and penetration tests at the P3 maintenance level
12.	cracks in the nodes of the bogie frame	damage of the construction structure, propagation of fatigue cracking in further operation	check and parametric cards in the MSD of the bogie frame rail vehicle maintenance manual Ct-3	1	6	4	**24**	visual assessment of the condition of the nodes of the bogie frame or penetration tests at the P3 maintenance level

In most cases, the risk level reaches RPN = 20 (Fig. 3, 4). A higher figure was found for:

- failures of brake elements $RPN_3 = 45$ ($O = 5$, $S = 3$, $D = 3$);
- failures of pneumatic conduits $RPN_7 = 30$ ($O = 5$, $S = 2$, $D = 3$);
- cracks in the nodes of the bogie support and frame RPN_{11}, $RPN_{12} = 24$ ($O = 1$, $S = 6$, $D = 4$).

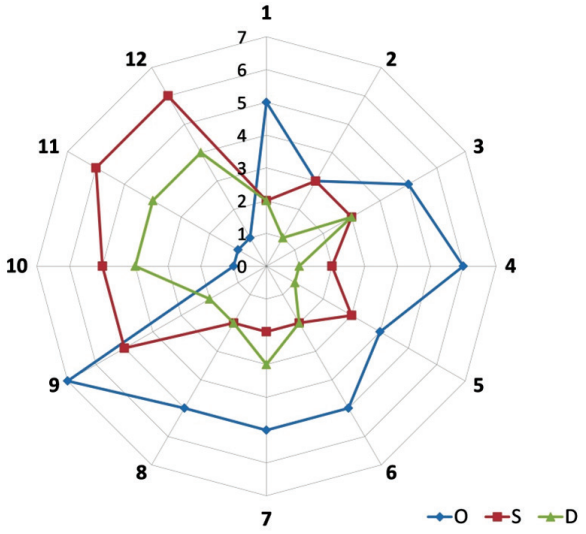

Fig. 3. Presentation of FMEA results – *O*, *S*, *D* parameters

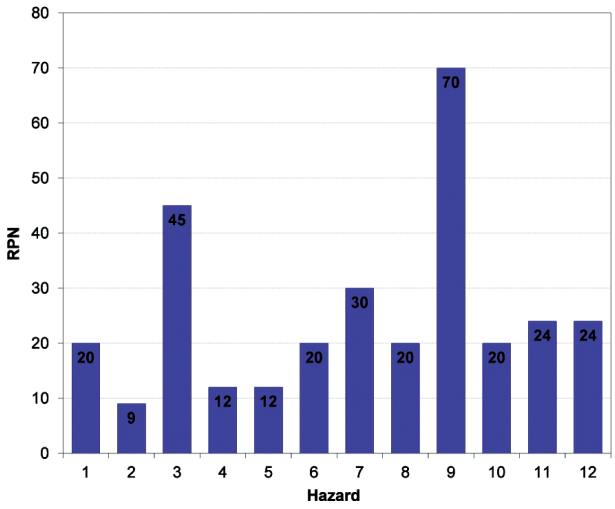

Fig. 4. Presentation of FMEA results – RPN figures for the particular hazards

Based on the conducted analysis, the possibility to make changes to the maintenance plan for 6Dg locomotives which would not be in breach of the acceptable safety level was shown. Nonetheless, changes to the locomotive maintenance plan require particular attention during the

performance of operation and repair work with regard to the assemblies and subassemblies which have a major effect on the safety of railway transport. These assemblies and subassemblies are:

- wheel sets,
- brake system,
- bogie support and frame.

Due to the considerable age of the locomotives' support structure, special attention should be placed on visual inspection and the checking of the structural nodes of the body's support and bogie frame. The following preventive safety measures were proposed:

- introduction, at the P2/1 maintenance level, of visual check activities on the structural nodes of the vehicle frame and bogie frame;
- at the P3 level, conducting of simplified flaw-detection tests of the wheel sets;
- performance of penetration tests of the structural nodes on the bogie support and frame during repairs at the P4 maintenance level;
- in the IT system supporting the management of the carrier's transporting potential, the possibility of ongoing monitoring of the technical condition of the locomotives should be taken into account.

7. Conclusion

FMEA is one of the many explicit risk estimation methods mentioned in Commission Implementing Regulation (EU) No. 402/2013. It establishes a systematic approach requiring knowledge of all types of failure that are either registered during operation or are anticipated. This paper has presented an example of its application based on changes in the maintenance system of the 6Dg type locomotive. Changes in the maintenance plan require maintenance system documentation to be updated for the operations and processes allocated to particular maintenance levels. The changes were the subject of an analysis of the applicable maintenance system documentation.

In accordance with Commission Regulation (EU) No. 1078/2012 of 16 November 2012 on a common safety method for monitoring, the effectiveness of the taken control measures or preventive measures should be monitored and supervised and their effects should be verified. The regulation obliges railway undertakings and entities in charge of maintenance to ensure the exchange of relevant safety information identified in the monitoring process. After the specified time of operation of the control measures, the process should be evaluated and the new RPN risk indicator should be calculated. Preventive actions proposed during hazard identification and risk assessment by the FMEA method should be used as the input data to the safety improvement program.

The next stage of works related to the change of the maintenance strategy of the analysed locomotive should be the assessment of the effectiveness of the proposed changes using the life cycle costs (LCC) analysis. It can be particularly useful to compare the maintenance costs in the full maintenance plan of the locomotive and compare the unit maintenance costs before and after the proposed changes.

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An analysis of fast-changing phenomena in the cutting zone during the turning of a Ti-6Al-4V titanium alloy shaft

Analiza zjawisk szybkozmiennych w strefie skrawania podczas toczenia wałka ze stopu tytanu Ti-6Al-4V

Abstract
This paper presents an experimental method of determining the velocity of chip flow on the rake surface of a cutting insert during the longitudinal turning of Ti-6Al-4V titanium alloy. A Seco CNMG120408-M1 833 carbide cutting insert without a protective coating was used for the purposes of research. In order to record phenomena in the cutting zone, a PHANTOM V5.2 high-speed camera was used and placed above the area of machining. The camera recorded the process at a speed of 3000 fps. Placing the camera near the cutting zone allowed recording the process of chip formation and its flow along the rake face of the insert. Trials of longitudinal turning were performed in accordance with the test plan, where v_c and f were the independent variables. In addition, the tests were performed for two different cutting depths. Processing and analysis of the obtained video sequences were performed with the use of CineViewer 663 and Tracker computer applications. Experimental determination of the velocity of chip flow at the rake face of a cutting insert was conducted by analysing the movement of the characteristic point on the outside side of the chip. Analysis of variance for the obtained results was performed using ANOVA and the regression functions were determined.

Keywords: Ti-6Al-4V, fast-changing phenomena, ANOVA

Streszczenie
W artykule przedstawiono eksperymentalny sposób wyznaczania prędkości spływu wióra po powierzchni natarcia płytki skrawającej podczas toczenia wzdłużnego stopu tytanu Ti-6Al-4V. W ramach badań wykorzystano płytkę skrawającą z węglika spiekanego, bez powłoki ochronnej, Seco CNMG120408-M1 833. Do rejestracji zjawisk w strefie skrawania zastosowano kamerę szybkoklatkową PHANTOM V5.2 umieszczoną nad strefą obróbki. Szybkość rejestracji kamery wynosiła 3000 kl/s. Ustawienie kamery w tym miejscu umożliwiało rejestrację procesu powstawania i spływu wióra po powierzchni natarcia płytki. Próby toczenia wzdłużnego realizowano zgodnie z przyjętym planem badań, gdzie zmiennymi niezależnymi były v_c i *f*. Dodatkowo próby wykonano dla dwóch różnych głębokości skrawania. Obróbkę i analizę otrzymanych sekwencji wideo przeprowadzono w aplikacjach komputerowych CineViewer 663 oraz Tracker. Eksperymentalne wyznaczenia prędkości spływu wióra na powierzchni natarcia płytki skrawającej realizowano przez analizę ruchu punktu charakterystycznego na zewnętrznej stronie wióra. Dla uzyskanych wyników przeprowadzono analizę wariancji ANOVA i wyznaczono funkcje regresji.

Słowa kluczowe: Ti-6Al-4V, zjawiska szybkozmienne, ANOVA

1. Introduction

Machining is one of the most common techniques for manufacturing parts of machines and devices. At present, in addition to meeting high requirements with regard to dimensional and shape accuracy of objects made, great attention is paid to achieving high levels of production efficiency. When using CNC machines, the proper selection of cutting parameters is a very important factor that allows the achievement of high production efficiency [1, 2]. In the automotive and aerospace industries, titanium and its alloys are commonly used materials. Due to its low coefficient of thermal conductivity and a tendency to cure under the influence of heat (precipitation hardening), titanium belongs to the group of difficult-to-cut materials. A lot of space in literature is devoted to the analysis of physical phenomena that occur in the cutting zone when machining these materials [3, 4]. Such phenomena have an impact on the form of the chip generated during machining [5–8, 10]. This article focuses on issues related to the process of creating and shaping the chip. Both the conditions in which the formation of chips occurs and their form have a significant impact on the safety, reliability and efficiency of the cutting process as well as on the features of the surface layer of the processed workpiece. Analysis of the process of chip formation is a complex issue. This is mainly related to the variable area of contact between the chip and the tool. Rapid development in the field of chip breaking is associated with dynamic progress in the construction of indexable inserts [5–8]. Manufacturers of cutting tools are increasingly devoting significant funds to research aimed at improving the design and specialisation of tools [3, 9, 11]. Currently, great attention is being paid to the implementation of new, specially shaped chip breakers. Modern solutions are aimed at forcing the chip to be directed to the untreated surface of the workpiece or towards the flank surface of the tool in such a way that it has a desired shape and breaks down quickly.

2. Conducted research

Laboratory tests consisted of the longitudinal turning of a shaft made of Ti-6Al-4V titanium alloy. The diameter of the shaft was D = 60 mm. The test stand comprised a Knuth Masterturn 400 lathe, a Phantom v5.2 high-speed camera placed above the cutting zone, a Dedocool spot illumination system, and a computer with Cine 663 software. The cutting tool was mounted in a single-position tool post (Fig. 1).

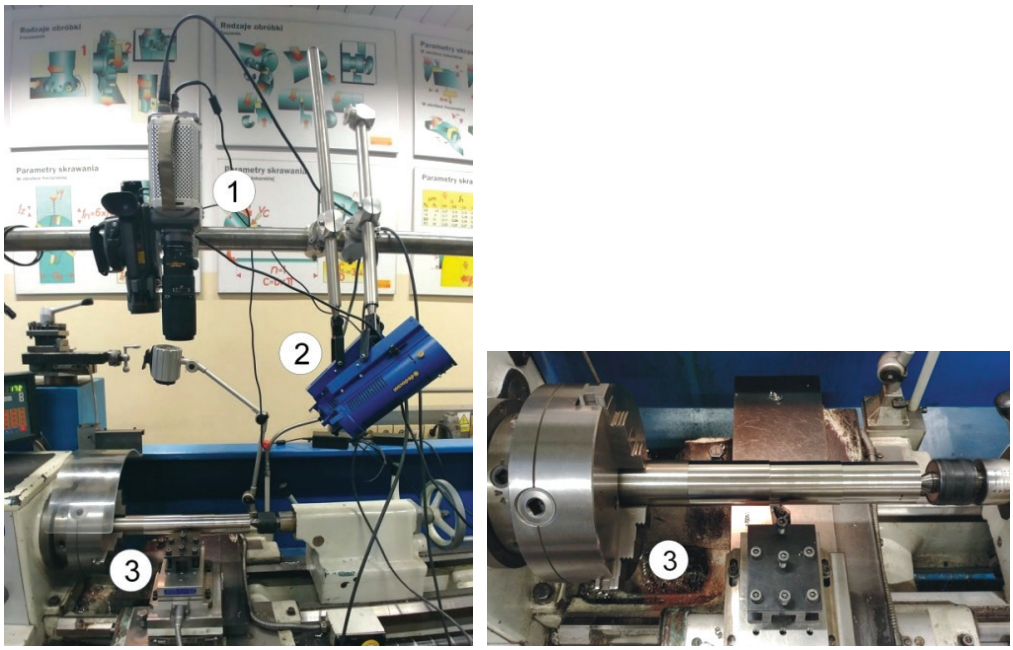


Fig. 1. The test stand: 1 – Phantom v5.2 high-speed camera placed in front of the cutting zone, 2 – spot illumination system Dedocool, 3 – tool position in relation to the workpiece

Table 1 presents the configuration parameters of the PHANTOM v 5.2 high-speed camera.

Table 1. The configuration parameters of the PHANTOM v 5.2 high-speed camera

resolution	512x512 – 8 bit
sensor	CMOS
frame rate	3000 fps
memory	4 GB
distance measurement	1.0 m

Figure 2 shows a NIKKOR 200 mm prime lens which was used to record the fast-changing images. Figure 3 presents the Dedocool spot illumination system, model Coolt3.

Fig. 2. NIKON Nikkor AF Micro 200 mm f/4D

Fig. 3. Dedocool spot illumination system, model Coolt 3

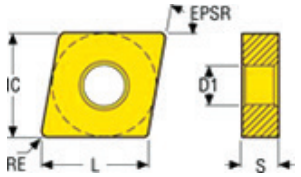
The chemical composition of Ti-6Al-4V titanium alloy is shown in Table 2.

Table 2. Chemical composition of Ti-6Al-4V titanium alloy

Al. [%]	V [%]	Fe [%]	O [%]	C [%]	N [%]	H [%]	Ti
min 5.50 max 6.75	min 3.50 max 4.50	max 4.50	max 4.50	max 4.50	max 4.50	max 4.50	rest

The tool that was used during the trials was a SECO turning tool consisting of a non--coated carbide insert, marked as CNMG120408-M1 833 and a DCLNR2525M12-M tool holder. The geometric parameters of the cutting insert used are shown in Table 3.

Table 3. Geometric parameters of the cutting insert used



Name	Description	Value
D1	fixing hole diameter	5.2 mm
EPSR	insert angle	80°
IC	inscribed circle diameter	12.7 mm
L	theoretical cutting edge length	12.9 mm
RE	corner radius	0.8 mm
S	insert thickness	4.76 mm

The profiles of the rake surface of the insert used are presented below; these are measured in the tool coordinate system at distances of 1.25 and 2.5 mm from its top (Fig. 4a). The measurement was made on a Taylor Hobson Intra 50 digital profilograph. The values of rake angles were determined at a distance of 0.4 mm from the cutting edge for the obtained cross sections (Fig. 4b).

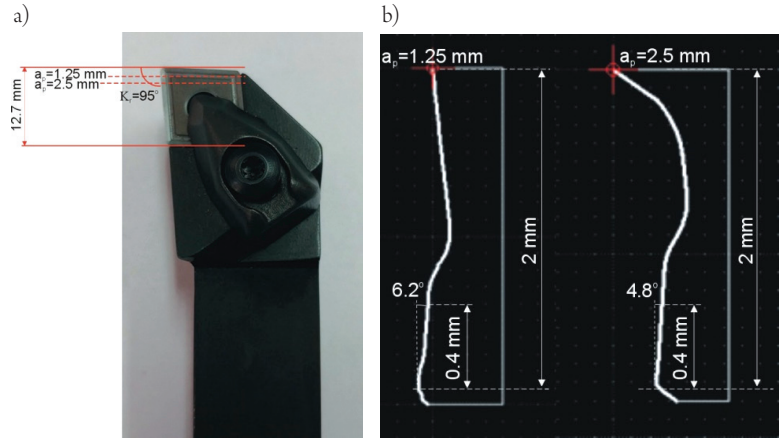


Fig. 4. Rake surface profiles measured at cut depths of a_p = 1.25 mm and a_p = 2.5 mm

3. Findings

The research plan was based on an L9 orthogonal table; there were two independent factors, each with three different values. The independent factors in the tests were: v_c – cutting speed, f – feed. Parameters v_c and f were assumed respectively as independent variables A and B. The ranges of variation of the cutting parameters were determined on the basis of catalogue data. Table 4 presents the assumed values of the cutting parameters.

Table 4. Values of cutting parameters

Symbol	Cutting parameters	Parameter values		
A	v_c [m/min]	18	25	32
B	f [mm/rev]	0.153	0.230	0.307

The parameter values for the individual trials are given in the table below (Table 5).

Table 5. The parameter values for individual trials

Test no.	A	B	v_c [m/min]	f [mm/rev]
1	1	1	18	0.153
2	1	2	18	0.230
3	1	3	18	0.307
4	2	1	25	0.153
5	2	2	25	0.230
6	2	3	25	0.307
7	3	1	32	0.153
8	3	2	32	0.230
9	3	3	32	0.307

A series of longitudinal turning operations was additionally performed for two cutting depth values: a_p = 1.25 and 2.5 mm. Every turning operation was recorded using a high-speed camera. A Phantom high speed camera with a Nikon 200 mm lens was used to record the process of chip formation. The recording duration was 4 s with a of 3000 fps, and a resolution of 512 x 512 px. Several-frame fragments were extracted from the recorded sequences with a use of Cine software. Presented below are examples of analyses obtained for: trial no. 1 (a_p = 1.25 mm, v_c = 18 m/min, f = 0.153 mm/rev) – Fig. 5; trial no. 3 (a_p = 2.5 mm, v_c = 18 m/min, f = 0.307 mm/rev) – Fig. 6. The different forms of chips obtained for different feed values are visible.

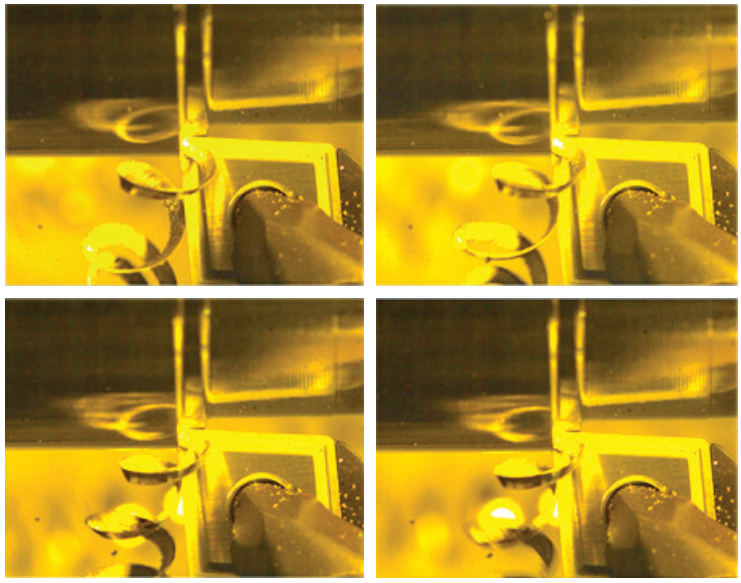


Fig. 5. Example images from trial no. 1

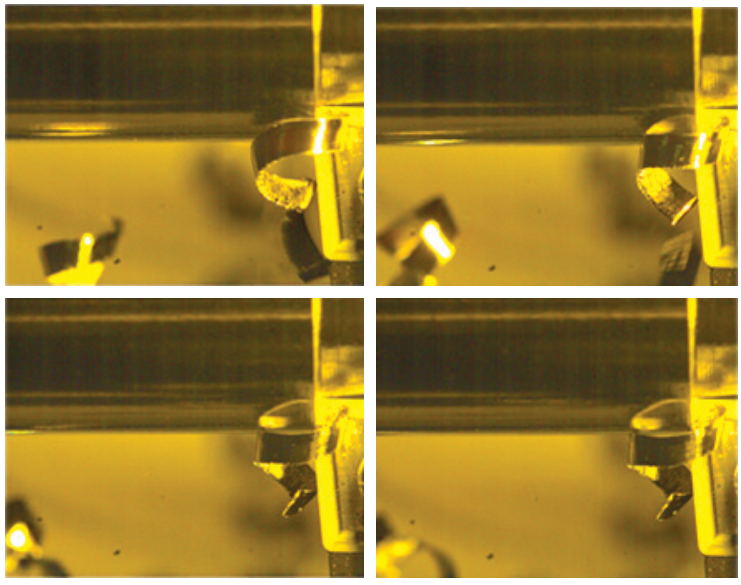


Fig. 6. Example images from trial no. 3

It was important to ensure that the selected video sequence was not overexposed, and that the chip flowing down the rake surface had a specific point that could be used as a marker in the analysis process. In practice, it was difficult to indicate specific points on the flowing chips for individual trials; this was related to the reflection of light from the surface of the chip. Filters were a helpful tool for eliminating this issue. An example of the use of filters in the CineViewer663 software is shown below (Fig. 7).

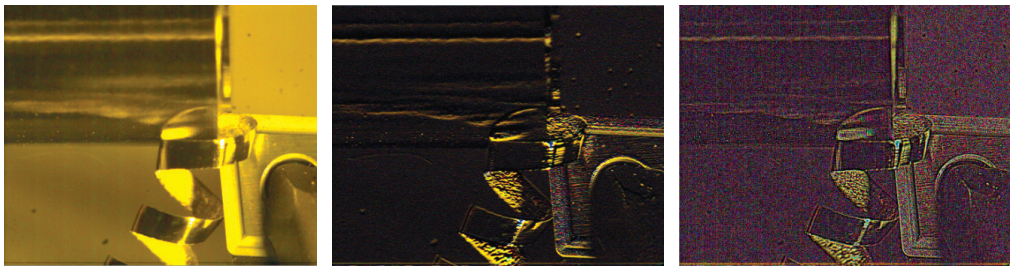


Fig. 7. Example use of filters in the CineViewer 663

Following the procedure outlined above, Tracker software was used; this enables the analysis of the movement of a given point. By using the 'Point Mass' tool, and based on the time-lapse analysis of the position of the specific point on the chip, average velocities with which the chip floats on the face of the tool's rake were determined (Figs. 8 and 9). It should be noted that in order to determine the average velocity of flowing chips accurately, it was necessary to specify the reference dimension in the analysed photographs each time. Such a dimension was the length of the working part of the tool.

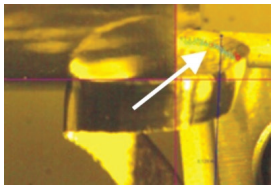


Fig. 8. Analysis of the position of the specific point on the chip

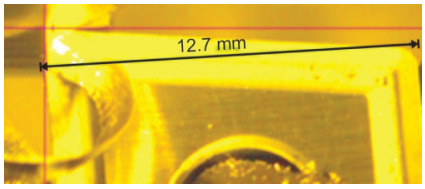


Fig. 9. The reference dimension in the analysed photographs

By analysing the movement of the specific point on the chip, the average velocity of its flow on the rake face of an insert v_{ch} [m/min] was determined. The obtained values of the chip flow velocity, determined for two cutting depths, are listed below in Table 6.

Table 6. Obtained values of the chip flow velocity determined for two cutting depths

Test no.	A	B	v_c [m/min]	f [mm/rev]	a_p = 1.25 mm	a_p = 2.5 mm
					v_{ch} [m/min]	
1	1	1	18	0.153	16.5	12.4
2	1	2	18	0.230	15.1	14.7
3	1	3	18	0.307	18.0	13.1
4	2	1	25	0.153	18.6	18.2
5	2	2	25	0.230	16.8	19.3
6	2	3	25	0.307	19.6	15.3
7	3	1	32	0.153	22.8	22.2
8	3	2	32	0.230	27.0	22.0
9	3	3	32	0.307	28.6	26.8

Figures 10 and 11 show the influence of the particular cutting data on the values of average chip flow velocity.

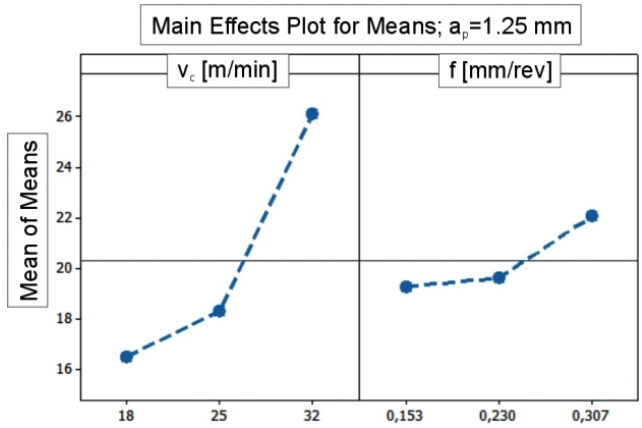


Fig. 10. The influence of the cutting data on the values of the average chip flow velocity (a_p = 1.25 mm)

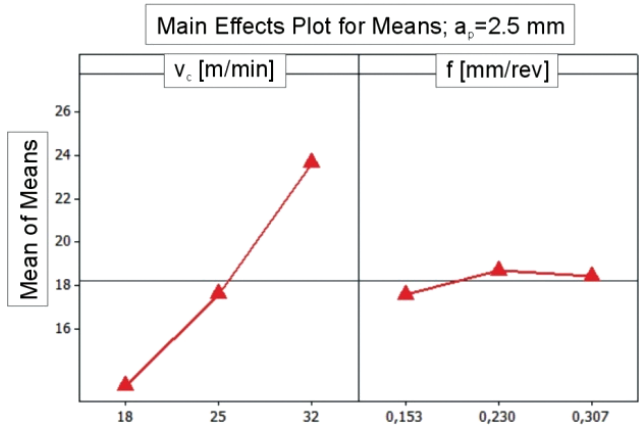


Fig. 11. The influence of the cutting data on the values of the average chip flow velocity (a_p = 2.5 mm)

Tables 7 and 8 present the statistical analysis of the test results (DF – degrees of freedom, Seq SS – sums of squares, Adj SS – adjusted sums of squares, Adj MS – adjusted means squares).

Table 7. Analysis of variance for average value v_{ch}, a_p = 1.25 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	p
f	1	11.514	11.514	11.514	2.112	0.196
v_c	1	138.071	138.071	138.071	25.329	0.002
residual error	6	32.707	32.707	5.451		
total	8	182.292				

Table 8. Analysis of variance for average value v_{ch}, a_p = 2.5 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	p
f	1	0.954	0.954	0.954	0.212	0.661
v_c	1	157.202	157.202	157.202	35.016	0.001
residual error	6	26.936	26.936	4.489		
total	8	185.092				

Equations $v_{ch}(f, v_c)$ for a_p = 1.25 mm (eq. 1) and a_p = 2.5 mm (eq. 2) are described below:

$$v_{ch}(f, vc) = -0.938755 + 17.9908 \cdot f + 0.685295 \cdot v_c \quad (1)$$

$$v_{ch} = -1.24343 + 5.17868 \cdot f + 0.731232 \cdot v_c \quad (2)$$

4. Conclusions

The research involved recording, in the form of video sequences, the process of chip formation and its flow on the rake surface of a cutting insert during the longitudinal turning of Ti-6Al-4V titanium alloy. A PHANTOM V5.2 high-speed camera was used for this purpose. Tests were performed in accordance with the adopted test plan. Video sequences were recorded at 3000 fps. Using the CineViewer 663 software, relevant fragments were selected for further analysis. In the subsequent part of the work, the average velocities of chip flow on the rake surface were determined with a use of Tracker software. For the obtained results an ANOVA was conducted and the v_{ch} regression equations (f, v_c) were determined. On the basis of the results, a strong influence of the cutting speed on the chip flow velocity was found for two examined depths of cut: a_p = 1.25 mm and a_p = 2.5 mm. An increase in the cutting speed results in an increase in the velocity of chip flow.

An increase in feed rate had a much smaller impact on the increase in the value of the chip flow velocity than cutting speed. It was found that slightly higher values of chip flow velocity occur for a smaller depth of cut. This phenomenon may result from the fact that depending on the depth of cut there are various shapes of chip breaker. In the case of a smaller depth of cut, the chip had a continuous form in the shape of a ribbon and it did not break. For a_p = 2.5 mm, the chip was broken into sections by the insert's rake face and had the a shape of an arc.

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The experimental determination of cutting forces in a cutting zone during the orthogonal turning of a GRADE 2 titanium alloy tube

Eksperymentalne wyznaczanie sił w strefie skrawania podczas toczenia ortogonalnego rury z tytanu GRADE 2

Abstract

This article presents the results of laboratory tests involving the measurement of cutting forces during the orthogonal turning of a tube made of GRADE 2 titanium alloy. The nominal diameter of the turned tube was D = 60 mm, and its wall thickness was 2.77 mm. For research purposes, a Kennametal chisel with an insert marked A3G0500M05P04DF and a holder marked A3SAR2520M0425-075-100 was used. An experimental research plan for variable cutting parameters (f, v_c) was developed according to the Taguchi method and statistical analysis of the results was performed using an ANOVA. Three series of tests were performed, one for each of the three different values of tube wall thickness (a_p = 2.77, 1.77, 0.5 mm). In accordance with the prepared test plan, nine trials were conducted within each series. Cutting forces were measured during each test with the use of a 3-axis Kisler 9257B piezoelectric dynamometer. DynoWare computer software was used for the archiving and analysis of measurement results.

Keywords: GRADE 2, cutting forces, ANOVA

Streszczenie

Artykuł prezentuje wyniki badań laboratoryjnych pomiaru sił skrawania podczas toczenia ortogonalnego rury z tytanu GRADE 2. Nominalna średnica toczonej rury wynosiła D = 60 mm, natomiast grubość ścianki 2,77 mm. Do badań wykorzystano przecinak firmy Kennametal o oznaczeniu płytki A3G0500M05P04DF, zamontowanej w oprawce A3SAR2520M0425-075-100. Eksperymentalny plan badań dla zmiennych parametrów skrawania (f, v_c) opracowano według metody Taguchi, natomiast statystyczne opracowanie wyników wykonano za pomocą analizy ANOVA. W czasie prac zostały przeprowadzone trzy serie prób trzech różnych wartości grubości ścianki rury (a_p = 2,77; 1,77; 0,5 mm). W ramach każdej serii zgodnie z opracowanym planem badań wykonano 9 prób. Pomiar sił skrawania był realizowany w każdej próbie za pomocą 3-osiowego siłomierza piezoelektrycznego Kisler 9257B. Do archiwizacji i analizy wyników pomiarów zastosowano program komputerowy DynoWare.

Słowa kluczowe: GRADE 2, siły skrawania, ANOVA

1. Introduction

A properly conducted cutting process should guarantee high product quality and adequate tool durability [2–5]. Ensuring such a process requires the correct identification of the cutting zone status [1, 6]. The machining process is characterised by the following basic physical phenomena: large plastic deformations in the zone of concentrated tangential stresses; the movement of some of the workpiece material in the form of chips along the rake surface of the tool under conditions of varying mechanical and thermal stress; moving of some of the workpiece material along the flank surface of the tool, thus forming a machined surface [8, 9]. Proper analysis of the cutting zone performed in the design phase and during the selection of cutting tools is an important factor in order to select the best possible material configuration between the tool and the workpiece, and to determine the most appropriate tool stereometry [2, 3, 5, 8]. Experimental methods and methods based on theoretical models are used in the analysis of the machining zone [7]. Regardless of the choice of method, it is necessary to have knowledge about the phenomena that occur during the process of machining. Indicators coming from the cutting zone, such as the values of the cutting forces, the level of acoustic emission, thermal radiation and vibrations should be identified. On basis of these values, it is possible to control the cutting parameters [1, 9].

2. Conducted research

The laboratory stand was assembled with a set of measuring instruments used to record the components of the total cutting force. The arrangement of these instruments is presented in Fig. 1.

1. KISTLER 9257B 3 axis piezoelectric dynamometer,
2. KISTLER type 5070A multi-channel charge amplifier,
3. PC with a DynoWare software.

Fig. 1. The arrangement of measuring instruments used to record the components of the total cutting force

The cutting forces were recorded with a frequency of 1000 Hz. Such a measurement path enabled measurements of the components of the total cutting force with the following levels of inaccuracy: F_f (feed force) ±0.25 N and F_c (tangential force) ±1 N. Tool position in relation to the workpiece is presented in Fig. 2.

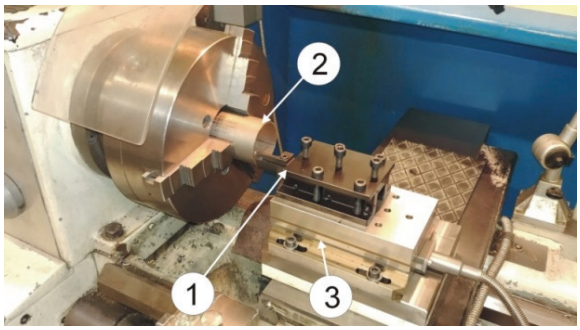


Fig. 2. Tool position in relation to the workpiece

where:

1. single-position tool holder with the insert installed,
2. a tube made of GRADE 2 titanium, diameter D = 60 mm,
3. a dynamometer mounted on the lathe slide.

A Kennametal chisel with an insert marked A3G0500M05P04DF and a holder marked A3SAR2520M0425-075-100 were used for the tests. The insert was made of KC5010 carbide with TiAlN coating. No coolant was used during the turning process. A photograph of the tool and 3D views of its face are shown below in Fig. 3. The presented 3D views were created by arranging successive 2D photos taken with the Keyence VHX-600 laboratory microscope. The face of the insert has a chip breaker and is characterised by a complex, symmetrical geometry.

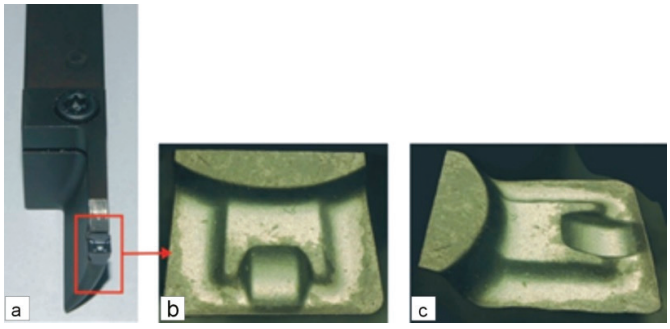
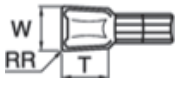


Fig. 3. a) The Kennametal tool, b) top and c) side views of the rake face

Geometrical dimensions of the A3G0500M05P04DF insert are shown in Table 1.

Table 1. Geometrical dimensions of A3G0500M05P04DF insert

	W [mm] RR [mm] T [mm]
	5.00 0.4 4.5

On the basis of preliminary tests performed for the depth (width) of cutting a_p = 2.77 mm, a characteristic forms of the internal side of the chip associated with different velocities of its runoff on the tool face were observed (Fig. 4). Areas A and B were measured and determined on the chip and on the face of the insert. The widths of areas A on the rake face were 0.5 mm, while the width of area B was 1.77 mm.

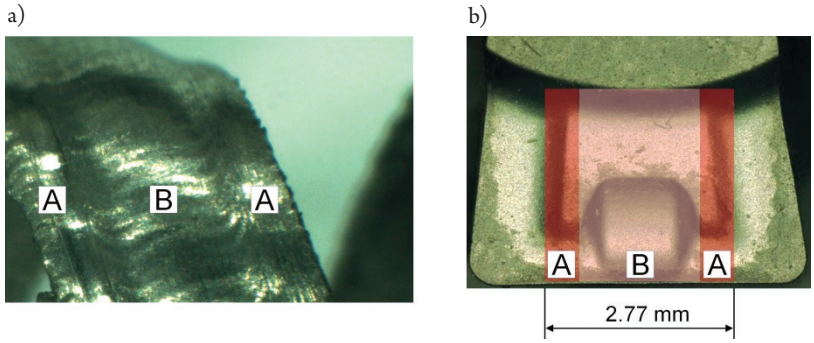


Fig. 4. a) Characteristic areas A and B on the chip surface and b) corresponding areas on the rake face of the insert

The workpiece was a tube made of GRADE 2 titanium alloy, diameter D = 60 mm. The chemical composition of the GRADE 2 titanium alloy, in accordance with the EN 10204-3.1 standard, is presented in Table 2.

Table 2. The percentage chemical composition of GRADE 2 titanium alloy

	Fe	C	N	O	H	Ti
GRADE 2 max.	0.30	0.08	0.03	0.25	0.015	Bal.

Some properties of GRADE 2 titanium alloy are presented in Table 3.

Table 3. The properties of GRADE 2 titanium alloy

Melting Point	ca.1660 [°C]
Density	4510 [kg*m^{-3}]
Modulus of Elasticity	105 [GPa]
Specific Heat Capacity	526 [J*kg^{-1}*K^{-1}]
Thermal Conductivity	16.4 [W*m^{-1}*K^{-1}]

3. Findings

Three series of tests were performed for three different values of pipe wall thickness (a_p = 2,77; 1,77; 0,5 mm). A research plan was generated using the Taguchi method. In accordance with the prepared test plan, nine trials were conducted within each series.

Parameters f and v_c were adopted as independent variables A and B, respectively. Ranges of variation of cutting parameters were determined on the basis of catalogue data. Table 4 presents assumed values of the cutting parameters.

Table 4. Values of cutting parameters

Symbol	Cutting parameters	Parameter values		
A	f [mm/rev]	0.048	0.153	0.249
B	v_c [m/min]	60	100	140

The parameter values for the individual trials are given in the table below (Table 5).

Table 5. The parameter values for individual trials

Test no.	A	B	f [mm/rev]	v_c [m/min]
1	1	1	0.048	140
2	1	2	0.048	100
3	1	3	0.048	60
4	2	1	0.153	140
5	2	2	0.153	100
6	2	3	0.153	60
7	3	1	0.249	140
8	3	2	0.249	100
9	3	3	0.249	60

At the stage of statistical analysis of the results, the S/N ratio was determined, the smaller-the-better criterion was adopted. According to Taguchi, this type of coefficient is used when it is appropriate to minimise some of the undesirable features of the product. The S/N ratio was calculated from the formula:

$$\frac{S}{N} = -10 \cdot log\left(\frac{1}{2}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

In accordance with the adopted test plan, the components of the total cutting force were measured. The influence of the variable cutting parameters (f and v_c) on the values of the total cutting force components (i.e., feed F_f and tangential F_c) was analysed. Tables 6, 9 and 12 present the obtained results of the S/N parameter and the average values of the individual components obtained in the individual tests system. Figures 5–10 graphically show the influence of specific cutting data on the values of the cutting force components.

Tables 7, 8, 10, 11, 13 and 14 present the statistical analysis of the test results (DF – degrees of freedom, Seq SS – sums of squares, Adj SS – adjusted sums of squares, and Adj MS – adjusted means squares).

Table 6. The obtained results of the S/N parameter and the average values of the individual components (a_p = 2.77 mm)

Test no.	v_c [m/min]	f [mm/rev]	a_p = 2.77 mm			
			S/N F_f	$F_{f\ mean}$ [N]	S/N F_c	$F_{c\ mean}$ [N]
1	140	0.048	–45.0	177.8	–47.5	236.2
2	100	0.048	–45.6	190.1	–46.5	179.2
3	60	0.048	–44.2	161.3	–47.4	234.0
4	140	0.153	–47.4	234.4	–55.2	573.8
5	100	0.153	–47.8	245.3	–55.3	578.5
6	60	0.153	–47.9	248.7	–55.3	578.3
7	140	0.249	–48.4	261.1	–58.3	825.4
8	100	0.249	–49.5	296.7	–58.5	840.2
9	60	0.249	–49.7	303.0	–58.5	842.3

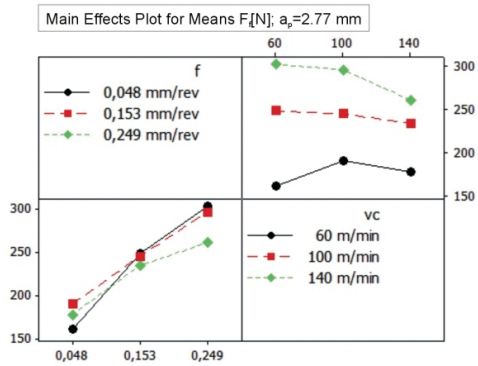


Fig. 5. The influence of the cutting data on the values of the cutting force components F_f, a_p = 2.77 mm

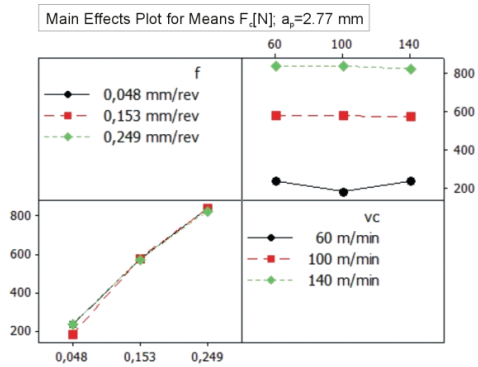


Fig. 6. The influence of the cutting data on the values of the cutting force components F_c, a_p = 2.77 mm

Equations $F_f(f, v_c)$ and $F_c(f, v_c)$ for a_p = 2.77 mm are described below as Equations 2–3, respectively:

$$F_f(f, v_c) = 114.804 + 914.078 \cdot f + 0.379144 \cdot v_c - 3.63040 \cdot f \cdot v_c \quad (2)$$

$$F_c(f, v_c) = 70.2319 + 3206.02 \cdot f + 0.0975940 \cdot v_c - 1.18581 \cdot f \cdot v_c \quad (3)$$

Table 7. Analysis of variance for average value F_f, a_p = 2.77 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	*p*
f	1	55240.4	55240.4	55240.4	85.28	0.000
v_c	1	788	736.8	736.8	1.14	0.297
f^*v_c	1	2557.6	2557.6	2557.6	3.95	0.059
residual error	23	14899	14899	647.8		
total	26	73485.1				

Table 8. Analysis of variance for average value F_c, a_p = 2.77 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	*p*
f	1	1734172	1734172	1734172	524.83	0.000
v_c	1	186	177	177	0.05	0.819
f^*v_c	1	273	273	273	0.08	0.776
residual error	23	75998	75998	3304		
total	26	1810629				

Table 9. The obtained results of the S/N parameter and the average values of the individual components (a_p = 1.77 mm)

Test no.	v_c [m/min]	f [mm/rev]	a_p = 1.77 mm			
			S/N F_f	$F_{f\ mean}$ [N]	S/N F_c	$F_{c\ mean}$ [N]
1	140	0.048	–41.8	122.0	–44.3	162.8
2	100	0.048	–42.2	128.8	–44.6	169.1
3	60	0.048	–42.9	138.8	–44.9	175.9
4	140	0.153	–43.6	150.3	–51.8	386.1
5	100	0.153	–44.3	163.4	–51.4	369.2
6	60	0.153	–45.4	184.6	–52.2	404.3
7	140	0.249	–44.7	170.9	–55.0	560.0
8	100	0.249	–45.7	190.5	–55.0	561.0
9	60	0.249	–46.6	212.8	–55.3	579.5

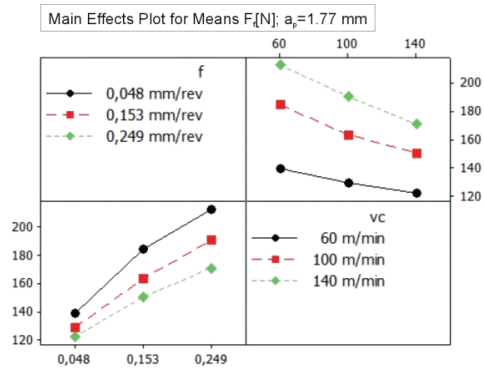


Fig. 7. The influence of the cutting data on the values of the cutting force components F_f, a_p = 1.77 mm

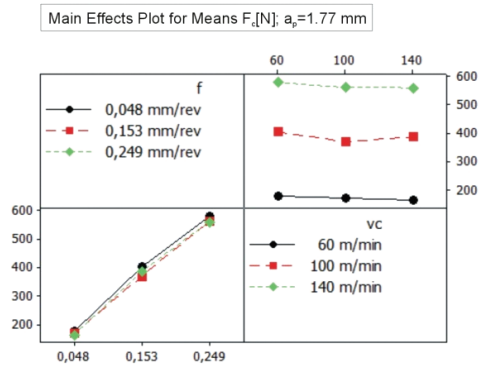


Fig. 8. The influence of the cutting data on the values of the cutting force components F_c, a_p = 1.77 mm

Equations $F_f(f, v_c)$ and $F_c(f, v_c)$ for a_p = 1.77 mm are described below as Equations 4–5, respectively:

$$F_f(f, v_c) = 131.599 + 464.212 \cdot f - 0.151348 \cdot v_c - 1.57527 \cdot f \cdot v_c \quad (4)$$

$$F_c(f, v_c) = 92.4486 + 2019.48 \cdot f - 0.151347 \cdot v_c - 0.401207 \cdot f \cdot v_c \quad (5)$$

Table 10. Analysis of variance for average value F_f, a_p = 1.77 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	*p*
f	1	17111.2	17111.2	17111.2	48.59	0.000
v_c	1	4327.6	4273.6	4273.6	12.14	0.002
f^*v_c	1	481.5	481.5	481.5	1.37	0.254
residual error	23	8099.7	8099.7	352.2		
total	26	30020				

Table 11. Analysis of variance for average value F_c, a_p = 1.77 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	*p*
f	1	712765	712765	712765	369.91	0.000
v_c	1	1289	1289	1289	0.66	0.423
f^*v_c	1	31	31	31	0.02	0.900
residual error	44318	44318	1927			
total	758402					

Table 12. The obtained results of the S/N parameter and the average values of the individual components (a_p = 0.5 mm)

Test no.	v_c [m/min]	f [mm/rev]	a_p = 0.5 mm			
			S/N F_f	$F_{f\ mean}$ [N]	S/N F_c	$F_{c\ mean}$ [N]
1	140	0.048	–32.6	42.1	–37.2	71.6
2	100	0.048	–32.4	41.3	–34.4	51.5
3	60	0.048	–32.5	41.3	–35.0	55.5
4	140	0.153	–36.3	64.0	–42.1	124.9
5	100	0.153	–38.9	86.1	–43.6	147.5
6	60	0.153	–39.7	90.8	–43.9	153.7
7	140	0.249	–39.1	87.1	–45.9	194.0
8	100	0.249	–40.7	105.7	–44.7	167.1
9	60	0.249	–42.8	135.7	–49.2	284.3

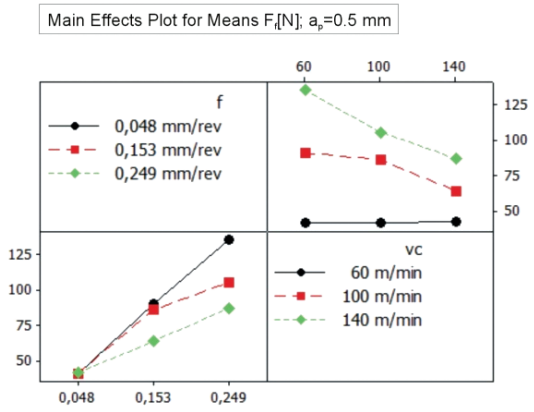


Fig. 9. The influence of the cutting data on the values of the cutting force components F_f, a_p = 0.5 mm

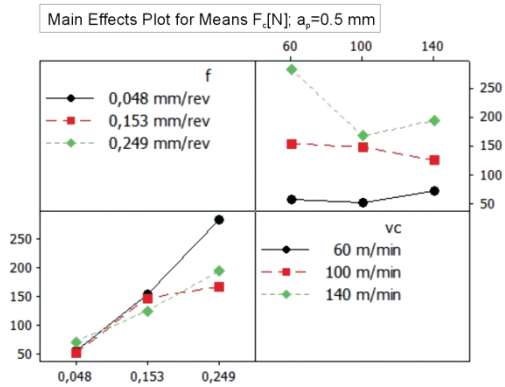


Fig. 10. The influence of the cutting data on the values of the cutting force components F_c, a_p = 0.5 mm

Equations $F_f(f, v_c)$ and $F_c(f, v_c)$ for a_p = 0.5 mm are described below as Equations 6–7, respectively:

$$F_f(f, v_c) = 11.2369 + 646.173 \cdot f - 0.151098 \cdot v_c - 3.07769 \cdot f \cdot v_c \quad (6)$$

$$F_c(f, v_c) = -33.3074 + 1434.19 \cdot f - 0.560723 \cdot v_c - 6.59926 \cdot f \cdot v_c \quad (7)$$

Table 13. Analysis of variance for average value F_f, a_p = 0.5 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	*p*
f	1	20833.7	20833.7	20833.7	44.06	0.000
v_c	1	2777.6	2694.7	2694.7	5.70	0.026
f^*v_c	1	1838.1	1838.1	1838.1	3.89	0.061
residual error	23	10875.3	10875.3	472.8		
total	26	36324.7				

Table 14. Analysis of variance for average value F_c, a_p = 0.5 mm

Source	DF	Seq SS	Adj SS	Adj MS	F	*p*
f	1	122816	122816	40939	27.53	0.000
v_c	1	109060	109060	109060	73.35	0.078
f^*v_c	1	8451	8451	8451	5.68	0.026
residual error	23	34199	34199	1487		
total	26	157015				

4. Conclusions

During the preliminary laboratory tests, the orthogonal turning of a tube made of GRADE 2 titanium alloy was performed. The nominal tube diameter was D = 60 mm and its wall thickness was 2.77 mm. The length of the cutting edge of the insert was 5 mm. The insert had a symmetrical chip breaker on the rake face. By analysing the internal shape of the obtained chips, three work areas of the chip breaker were defined: two symmetrically distributed areas, marked in the article in Fig. 4 as A, with a width of 0.5 mm; and the area marked as B, with a width of 1.77 mm. As part of the basic research, three series of orthogonal turning tests were performed. In two series, where the wall thickness of the pipe was 2.77 and 1.77 mm the workpiece was in contact with the central part of the plate (area B), while for the wall thickness of 0.5 mm with the area marked as A. Each series consisted of nine runs in which the independent variables were f and v_c. Two components of the cutting force were obtained for each series – the feed component F_f and the main component F_c. On the basis of the ANOVA, dependencies and regression equations were determined for the mean values of the cutting force components in the functions of f and v_c. For three cutting depths, the F_f component decreased with the increase in v_c. The decreasing trend of the F_f component value is particularly visible for higher feed rates (f = 0.249 mm/ rev and f = 0.153 mm/rev). An increase in v_c does not significantly change the F_c component. Higher values of the F_c component were obtained for larger feed values. The feed increase causes a linear increase in the F_f and F_c component values. Larger F_f values were observed for lower cutting speeds: v_c = 60 m/min and v_c = 100 m/min. The largest values of the cutting force components were obtained for the largest cutting depth a_p = 2.77, then 1.77 and 0.5 mm. The obtained dependencies will be used in further work to analyse the heat stream partition on the rake face of the insert.

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