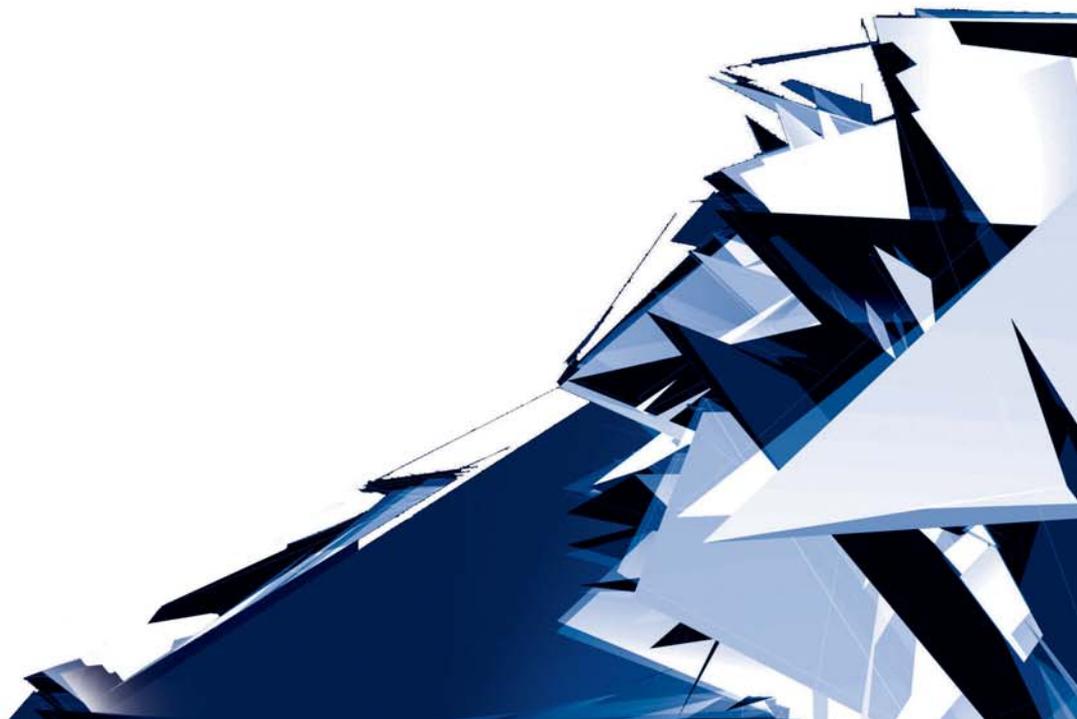


Technical Transactions

Czasopismo Techniczne

Issue 4

Volume 2018 (115)



Chairman of the Cracow University of Technology Press Editorial Board
Przewodniczący Kolegium Redakcyjnego Wydawnictwa Politechniki Krakowskiej

Tadeusz Tatara

Editor-in-chief
Redaktor naczelny

Józef Gawlik
(jgawlik@mech.pk.edu.pl)

Scientific Council
Rada Naukowa

Jan Blachut – University of Liverpool (UK)
Wojciech Bonenberg – Poznan University of Technology (Poland)
Tadeusz Burczyński – Silesian University of Technology (Poland)
Massimo Corcione – Sapienza University of Rome (Italy)
Leszek Demkowicz – The University of Texas at Austin (USA)
Joseph El Hayek – University of Applied Sciences (Switzerland)
Ameen Farooq – Technical University of Atlanta (USA)
Zbigniew Florjańczyk – Warsaw University of Technology (Poland)
Marian Gizejowski – Warsaw University of Technology (Poland)
Sławomir Gzell – Warsaw University of Technology (Poland)
Allan N. Hayhurst – University of Cambridge (UK)
Maria Kušnierova – Slovak Academy of Sciences (Slovakia)
Krzysztof Magnucki – Poznan University of Technology (Poland)
Herbert Mang – Vienna University of Technology (Austria)
Arthur E. McGarity – Swarthmore College (USA)
Antonio Monestiroli – Polytechnic of Milan (Italy)
Marek Pabich – Lodz University of Technology (Poland)
Ivor Samuels – University of Birmingham (UK)
Miroslaw J. Skibniewski – University of Maryland (USA)
Günter Wozny – Technical University in Berlin (Germany)
Roman Zarzycki – Lodz University of Technology (Poland)

Native Speakers

Weryfikacja językowa

Tim Churcher
Robin Gill
Justin Nnorom

Section Editor
Sekretarz Sekcji

Dorota Sapek
(dsapek@wydawnictwo.pk.edu.pl)

Editorial Compilation
Opracowanie redakcyjne

Aleksandra Urzędowska
(aurzedowska@pk.edu.pl)

Typesetting
Skład i lamanie

Małgorzata
Murat-Drożyńska

Design
Projekt graficzny

Michał Graffstein

Series Editors
Redaktorzy Serii

ARCHITECTURE AND URBAN PLANNING

Mateusz Gyurkovich
(mgyurkovich@pk.edu.pl)

CHEMISTRY

Radomir Jasiński
(radomir@chemia.pk.edu.pl)

CIVIL ENGINEERING

Marek Piekarczyk
(mpiekar@pk.edu.pl)

ELECTRICAL ENGINEERING

Piotr Drozdowski
(pdrozdow@usk.pk.edu.pl)

ENVIRONMENTAL ENGINEERING

Michał Zielina
(mziel@vistula.wis.pk.edu.pl)

**PHYSICS, MATHEMATICS
AND COMPUTER SCIENCES**

Włodzimierz Wójcik
(puwojcik@cyf-kt.edu.pl)

MECHANICS

Andrzej Sobczyk
(andrzej.sobczyk@mech.pk.edu.pl)

www.ejournals.eu/Czasopismo-Techniczne
www.technicaltransactions.com
www.czasopimotechniczne.pl

Contents

ARCHITECTURE AND URBAN PLANNING

Rafał Blazy

Concepts of transformations of cities – examples from the Silesian Agglomeration..... 5

Marcin Charciarek

Forms, details and contemporary meanings of Polish concrete architecture, part 1 23

Marcin Charciarek

Forms, details and contemporary meanings of Polish concrete architecture, part 2 35

Peter Gyori, Albert Fekete, Agnes Herczeg

Sight and insight – creating space for religious practices..... 45

Magdalena Rzeszotarska-Palka

Heavens above – a statue of Christ in the landscape 55

Dorota Wantuch-Matla

Microspaces – an outline of typological research based on examples from Krakow..... 69

CHEMISTRY

Krystian Leski, Przemysław Luty, Andrzej Łucki, Dawid Jankowski

Application of circulating fluidized bed boilers in the fuel combustion process..... 83

Dominika Misiura, Tomasz M. Majka

An overview on obtaining foamed PET by reactive extrusion..... 97

ELECTRICAL ENGINEERING

Volodymyr Samotyy, Ulyana Dzelendzyak, Andriy Pavelchak

An evolutionary model for the parametric optimisation of electromagnetic instruments of variable structures..... 103

Leonid Moroz, Volodymyr Samotyy

The CORDIC method of calculating the exponential function 119

Sergii Telenyk, Oleksandr Rolik, Eduard Zharikov, Yevhenii Serdiuk

Energy efficient data center resources management using beam search algorithm..... 127

MATHEMATICS

Adam Bednarz, Ludwik Byszewski

An abstract nonlocal functional-differential second order evolution Cauchy problem..... 139

MECHANICS

Patrycja Bazan, Stanisław Kuciel

The mechanical characterization of composites based on polyoxymethylene and the effect of silicone addition on the mechanical behaviour of manufactured composites..... 149

Stefan Chwastek

Selected aspects involved in the optimization of cranes with pivoting booms..... 159

Sławomir Kowalski

*The influence of a CrN+a-C:H:W coating on the development of fretting wear
in a model of a wheel-axle press-fit joint on a wheel set of a railway vehicle.....* 173

Pawel Lempa, Michal Ptaszynski, Fumito Masui

The use of genetic algorithm to optimize quantitative learner's motivation model 189

Karolina Mazur, Stanisław Kuciel

Composites based on recycled polystyrene waste with tuff microparticles 195

Rafał Blazy (rafal.blazy@pk.edu.pl)

Laboratory of Downtown Areas Design, Faculty of Architecture, Cracow University of Technology

CONCEPTS OF TRANSFORMATIONS OF CITIES
– EXAMPLES FROM THE SILESIA AGGLOMERATION

IDEE PRZEKSZTAŁCANIA MIAST
– PRZYKŁADY Z AGLOMERACJI ŚLĄSKIEJ

Abstract

The problem of functional, compositional, and structural transformations, necessary to be introduced in contemporary inner cities, is complex and multithreaded. Sometimes cities get compared to palimpsests – re-used parchments from which old texts were removed in order to replace them with new ones. Undoubtedly, they are very particular palimpsests, as it is very difficult to clearly assess what should be protected and preserved, and what can be replaced or reconstructed. This paper discusses problems and concepts of transformations of selected city centres of the Silesian agglomeration, paying special attention to big comprehensive reconstructions of Katowice and Gliwice.

Keywords: Theory of urban design, concepts of reconstruction of cities, reconstruction of Silesian cities, reconstruction of Katowice, reconstruction of Gliwice, city centre revitalisation, future of cities, city forming

Streszczenie

Problem przekształceń funkcjonalnych, kompozycyjnych i strukturalnych, koniecznych do wprowadzenia we współczesnych śródmieściach, jest złożony i wielowątkowy. Miasta czasami porównuje się z palimpsestami, czyli pergaminami, z których, chcąc wykorzystać cenny podkład, usuwano dawne zapisy, aby je zastąpić nową treścią. Są one niewątpliwie palimpsestami szczególnymi, gdyż bardzo trudno jest jednoznacznie ocenić, co powinno podlegać ochronie i pozostawieniu, a co można zastąpić względnie przebudować. Artykuł omawia problemy i idee przekształcenia wybranych centrów miast aglomeracji śląskiej, zwracając szczególną uwagę na duże – kompleksowe przebudowy Katowic i Gliwic.

Słowa kluczowe: teoria projektowania miast, idee przebudowy miast, przebudowa miast śląskich, przebudowa Katowic, przebudowa Gliwic, rewitalizacja centrum, przyszłość miast, formowanie miasta

1. Introduction

Cornelis van Eesteren, a great theoretician and experienced urban planner, said years ago: "(...) cities can be neither better nor more orderly than societies which created them. This fact will be changed neither by the urban planner's knowledge nor his personal views. The city is as if a projection of the society, each city map constitutes a deposit left by a certain social system" [2, p. 33]. Therefore, what is the projection of the contemporary Polish society? There is no doubt it has been much divided and stratified, especially in recent times, and these properties are definitely discernible in towns and cities of today. In this respect, one of the most visible divisions in Polish towns and cities is the dissonance between the city centre and the inner city, or downtown area. This diversification is primarily based on functional differences occurring in these areas. Functional changes entail also changes in the form of the urban tissue and changes in the standards and quality of architecture. The second clear division is marked between the inner city and suburban residential areas, shaped by individual buildings. These zones are separated by an irregular and very enigmatic borderline, dividing – as it were – two different worlds.

It must be acknowledged after Barbara Bartkowicz that "(...) 45 years of socialist economy and the contemporary process of political transformation created mixed structures, incoherent in functional and spatial terms, with a lot of wasted areas. A significant property of Polish towns and cities is the blurring of the border of urban investment lands, evolving into chaotically urbanised rural areas" [4, p. 14].¹

"The degradation factor [...of these areas] is the growing spatial chaos, intensifying particularly in the last fifteen years of the political transformation, caused by uncoordinated investment activities nearly in all areas, even the ones subjected to legal protection. This refers to in particular:

- ▶ Chaotic road envelopes and the growing dispersion of development around towns and cities in rural areas,
- ▶ Location of large commercial structures within the areas of municipal greenery and in historic industrial complexes, as well as inside or around small towns.
- ▶ Destruction of greenery and substance around modernised traffic routes and interchanges (also multilevel ones) built within urban tissue, which do not solve any problems anyway, additionally contributing to the disintegration of the space, and essentially still introduce traffic into narrow city streets" [3, pp. 29–30].

In Silesia, many areas which are now located in the very centres of towns and cities, in the 19th and 20th century were used for industrial and warehousing purposes; furthermore, many city centres fell into decay, and sometimes were even devastated and degraded. The issue of their transformation constitutes a fundamental and strategic problem of reconstruction of towns and cities and of shaping of a new appearance of these organisms. In many cases it refers

¹ In the text cited Barbara Bartkowicz also observed as follows: "Such a role cannot be usually played by existing Studies (...), diversified in terms of their contents and character. Existing local development plans, drawn up selectively for small areas, will likewise prove to be of little use".

to the search of a new identity of cities, as well as to the creation of their new image. In this respect some cities try to outline and obtain a new image by means of subsequent investments.²

2. Situation of silesian towns and cities

Sometimes cities get compared to palimpsests – re-used parchments from which old texts were removed in order to replace them with new ones. Undoubtedly, they are very particular palimpsests, as it is very difficult to clearly assess what should be protected and preserved, and what can be replaced or reconstructed. Quite extensive contemporary comprehensive reconstructions of city centres in Katowice and Gliwice deserve special attention in this respect. In these territories the reconstruction of the road system constituted a key element of transformations of big parts of inner cities.

Katowice, the capital of Silesian Metropolis, has been modernised very dynamically and intensively in recent years. After over 6 years, in April 2017 the reconstruction along the line between the Market Square and the Roundabout was completed. This project cost over PLN 263 million, and it linked a part of the Old Town with the so-called Culture Zone, built in the vicinity of Spodek. This zone comprises the following entertainment and culture facilities: International Congress Centre, a new seat of the Polish National Radio Symphony Orchestra, and the new Silesian Museum. These facilities cost over PLN 1 billion. An investment that is in progress at the moment is two new office buildings near Spodek, erected in the area formerly occupied by the demolished DOKP tower in Katowice. These facilities are erected under the name of KTW (KTW is an abridged name of Katowice, used on plane tickets). At the same time, they constitute a very important element of the compositional project of Chorzowska street, along which such projects as Silesia City Center in Katowice and Silesia Business Park have been implemented. The route of this street was reconstructed and put into use in its new form in 2006, when a 657-metre-long tunnel was opened underneath Generała Ziętka Roundabout, and the roundabout itself was covered with a state-of-the-art dome (1200 m²), which hovers above a half of the platform of the roundabout. Thanks to the revitalisation of post-mining zones and owing to other investments implemented in the city centre, Katowice has experienced an enormous change and it has stopped being a city exclusively associated with heavy industry; undoubtedly, today it aspires to the title of the capital of the metropolis (Fig. 1).

Along with an attempt to be granted the title of the European Capital of Culture, an idea was conceived in Katowice to promote it as the City of Gardens. This motto relates to creating a specific image of the city in connection with specific spatial changes. It entails the municipal authorities' need to invest in gardens and to improve their quality. Green

² To a certain extent a city which is firmly founded on historic industrial structures is Zabrze. Many revitalisation processes in this city are focused on the creation of post-industrial heritage. Examples in this respect could be revitalisation projects of the Guido mine and elevator shaft top, "Queen Luiza" Mining Heritage Park, industrial elements introduced in Pieruszki square (formerly Wincenty Pstrowski square), construction of a playground in the form of a mine, the so-called Bajtel Gruba (Silesian: children's mine). Similar actions are undertaken in the nearby Ruda Śląska, with "Ficinus" workers' colony amongst structures revitalised recently.

elements are to play a decisive role in new and currently revitalised public spaces. The effect of promoting Katowice as the City of Gardens is the fact that more and more tourists, hearing that Katowice is a city of gardens, start to actively look for and visit public spaces in Katowice, which contributes to their popularity. Such a declaration made by the municipal authorities is also a certain commitment – more and more funds get allocated to the revitalisation of green and public areas in Katowice.

In 2015 the first speed limit zone was introduced in Katowice, with the permissible speed of 30 km/h. The 30 speed zone in Katowice aims to improve safety and to facilitate pedestrian and cycling traffic in the districts of Tysiąclecia Housing Estate and Ochojec. According to the municipal authorities' argumentation, the goal in this respect is to improve the attractiveness of the city and of living in it, as well as obtaining better safety standards.

The contemporary lack of spatial homogeneity in Katowice partly results from historical reasons, as well as from the spatial policy implemented in the last 70 years. Katowice is 150 years old, its structure consists of historical villages, colonies, and hamlets, along with the 19th-century block development intertwined between them and numerous random modernist projects. The space of Katowice is very heterogenous, one could even describe it as a mosaic. A study carried out in the second half of the 1970s by Bohdan Jałowiecki, focusing on the centre of Katowice, identified this place in the eyes of its residents as an area of occasional shopping and a great transport hub [7, pp. 162–167].

On the other hand, a study carried out by Tomasz Nawrocki in 2004 focusing on the perception of the central space of Katowice further confirmed very strong negative associations and connotations of this place. For 47% of respondents this space was significant exclusively as a transport hub, for 36% as a place of shopping, and 23% perceived only the administrative significance of the centre. Characteristically enough, 21% of respondents did not register any important and characteristic functions fulfilled by the centre, or claimed that Katowice was deprived of any centre whatsoever [11, pp. 255–260]. It has to be acknowledged, however, that the aforementioned new investments in the centre of Katowice still only complete a certain patchwork structure. This structure is very heterogenous, fragmentary, limited to demarcated areas of investments (Fig. 1 and Fig. 4).³

Gliwice has been undergoing significant transformations, as well. Only in the very heart of the city, near the railway station, a big transport hub is planned. It is to serve as a new city centre of some sort, located at the end of Zwycięstwa street, and commencing on the historic Market Square. The entire project is to consume PLN 125 million and it is to be completed by the end of 2020. Very important investments in Gliwice are the 'Podium' Hall and the recently completed reconstruction of the Cross-Regional Highway. The thorough change of the traffic system, caused by the introduction of the Cross-Regional highway in the centre of Gliwice, changed the way this part of the city functioned. Spaces which used to be linked,

³ If one wishes to build spatial relations, one should build urban tissue creating broader spatial interrelations. They could come into being by means of convergence of composition and combination of elements of the structure. Creation of references and a grid of relations between points, lines, areas (fields) located within the perimeter of the city (may) constitute a matrix for consolidation of the urban tissue. Proximity of individual fragments and urban complexes stimulates and generates helpful solutions of individual components of the city architectonics.

Katowice – Centre

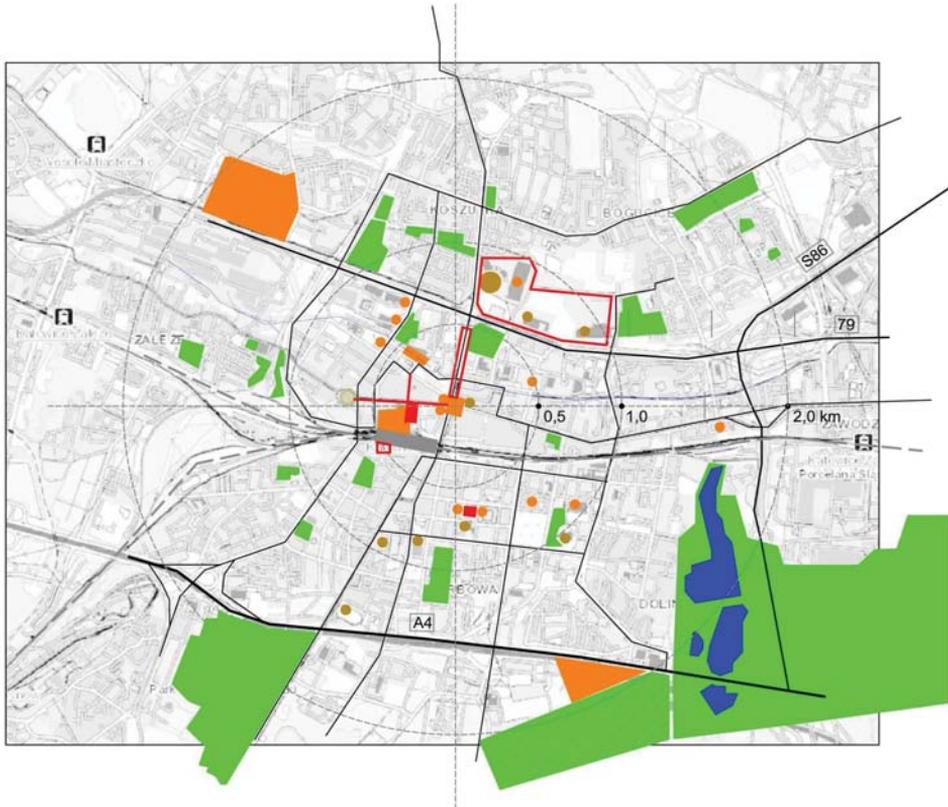
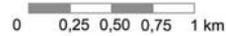


Fig. 1. Functional layout of Katowice with areas of revitalisation carried out in recent years (prepared by R. Blazy)

got separated and fragmented. In the places of former spatial barriers new – sometimes quite accidental – links and consolidations came into being, some buildings got uncovered, and some of them hidden behind acoustic screens. Smaller fragments of the urban tissue changed their mode of operation completely, at the same time changing their physiognomy, aesthetics, and principles of composition. This brought about a deep and quite unexpected transformation of the spatial and functional structure of the inner city.

Both city centres referred to above share one feature – they are intersected with new roads, built in locations which had been developed and urbanised before, sometimes in the places of old parks, historic factories, or tenement houses. The Cross-Regional Highway in Gliwice is said to “have gashed” the city centre (Fig. 2). The Cross-Regional Highway in Gliwice is perceived as a scar in the urban tissue. In historical terms, the centre of Chorzów has a similar experience – in 1979 a trestle bridge was built, intended for car traffic from Katowice to Bytom. This way Chorzów lost its historic Market Square, and today over 30 thousand cars

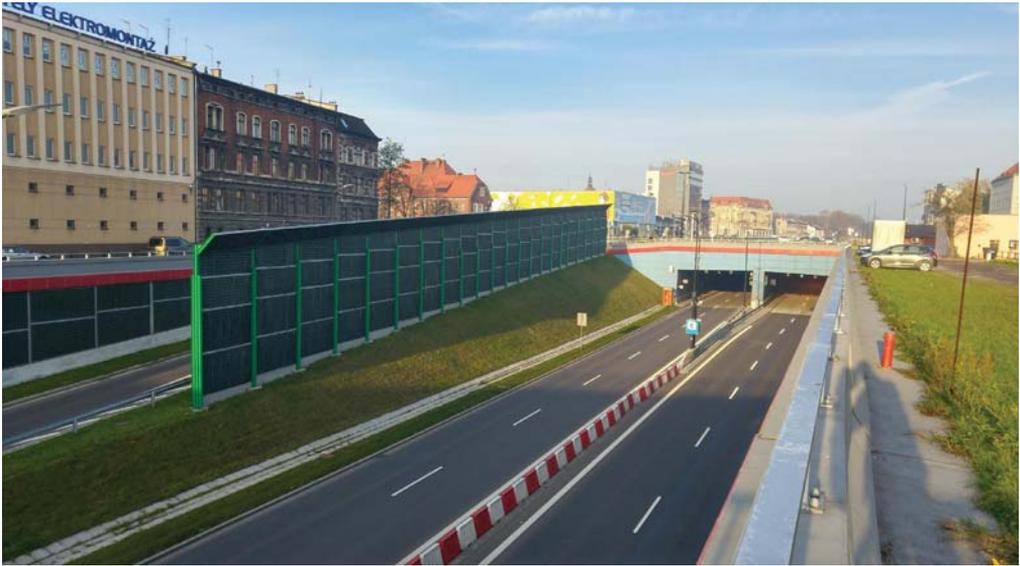


Fig. 2. “Concrete Cube 2015” anti-award went to the Cross-Regional Highway in Gliwice. “For dividing the city” (photo by R. Blazy)

drive this way every day. The central functions in Chorzów had to be taken over by Wolności street, modernised several years ago.

Currently, a very important reconstruction of the centre of Sosnowiec in the vicinity of 3 Maja street is planned. Several strategic investments have been planned along the road, such as a market square, which is to be built near the main railway station. The cost of one of the sections of the reconstruction is to reach more than PLN 60 million.

The period of the last 30 years connected with the multidimensional transformation of the Polish spatial reality results primarily from socio-political transformations and constitutes their consequence. Paradoxically, the contemporary capitalist economy cares more for making spaces pro-social than socialist authorities before. The social character of spatial solutions is one of the leading concepts accompanying the reconstruction of Polish cities over the last three decades. This pro-social approach aims to create spaces friendly for people due to their scale, interesting details, sometimes ornaments, friendly and ergonomic fittings. Street furniture catering for all sorts of human needs constitutes an essential component of reconstruction of the Polish urban space. Nevertheless, as it can be seen in Katowice, Gliwice, and Chorzów, if even less valuable development is removed, we are unable to perceive and evaluate contrasts existing between historic structures and their surroundings. Sometimes we are not even able to recognise entire former urban projects. These spaces start to play a completely different role in social terms, too. Frequently municipal authorities are not aware to what extent transformations of the urban tissue influence transformations of the life of the city.

It should be remembered that responsibility for the appearance of our towns and cities is not only borne by urban planners, investors, and decision makers, as when we look for relations between the law and the plan, we have to admit that it is the law that is the primary element deciding about the form the plans assume. It is the law that determines the rules governing plans. It is the law that allowed to build Place Stanislas in Nancy and the WZ route in Warsaw.

3. Ideas implemented in contemporary silesian cities

Ideas have always accompanied man. In most cases each of our actions is preceded by reflection. This reflection is connected with a vision which rises in us and which constitutes the initial motif in the process of creating spaces. In the case of space creation, it is a concept, an idea, the essence of the created or co-created intention. It is a seed which is the beginning of a plant, and in this case which provides the foundation for weaving a complicated structure of spatial links and functional – spatial – social relations. Each time a newly created urban tissue is grafted onto a certain concept. In principle, the contemporary Silesian solutions are based on the trend of postmodernist development concepts. In technical terms, they try to satisfy the requirements of sustainable development and economic effectiveness. Frank Lloyd Wright wrote that “ideas shape our reality”. Admittedly, ideas are undoubtedly the keynote in many our actions. Sometimes they are built around a specific architectural or cultural trend, sometimes they constitute a collection of ideas and goals which a given author or investor wishes to accomplish.

Contemporary revitalisations of Katowice, Gliwice, and Chorzów, although embedded in the existing urban tissue, do not inscribe into the concepts of contextualism, nor into the idea of a compact city. Continuing the thought cited, it should be stated that very often they do not refer with their assumptions in a clear and legible manner to the existing urban tissue. At the same time, the general concept is implemented predominantly by means of deconstructivist patterns and codes (Fig. 3), which quite often lead to spatial disintegration (development around the edifice of the Polish National Radio Symphony Orchestra, fragments of the revitalisation of the Market Square in Katowice, the building and development of the new railway station in Katowice, the solution of the Congress Centre near Spodek). Numerous publications, presenting deconstructivist visions, contribute to the popularity of this idea. A certain frequently observed feedback between the deconstructivist form of the urban plan and the lack of legibility and hierarchy in the spatial solution is quite conspicuous. The clash of the newly emerged urban tissue reveals different compositional concepts of the liberal architecture and neo-classical architecture.



Fig. 3. Deconstructivist concepts of organisation of the public space division near the edifice of the Silesian Museum in Katowice (photo by R. Blazy)

The contemporary disintegration of urban areas in the Silesian agglomerations results also from e.g. transforming streets and roads into traffic routes characterised by high capacity and traffic intensity. Quite often different actions are undertaken in the name of transport development and improvement, which in fact are not oriented towards creating a coherent urban space. Large-scale commercial and office facilities erected along transport routes become examples of insular urban planning (KTH, Silesia Business Center, National Polish Radio Symphony Orchestra). The overlapping social disintegration only intensifies

such phenomena. Frequently their users struggle with the lack of pedestrian access routes to individual functions. Regarding contemporary Silesian projects, it seems that transport functions develop at the expense of the loss of continuity of the spatial structure and at the expense of public functions (Fig. 2 and Fig. 4). The urban environment characterised by easy access for pedestrians, intensification of functions, human-friendly scale simply does not come into being at all. Two shopping centres should be regarded as exceptions from this rule in the Upper Silesian agglomerations: Forum in Gliwice, and Agora in Bytom.

Although according to many contemporary urban planners, in compliance with the transit oriented development principle (TOD) functions and development are to be intensified around transport hubs, still the practice and the reality of Silesian towns and cities demonstrates that – regrettably – such activities simply do not happen as far as designing the road system is concerned.⁴ And despite the fact that roads constitute an element on which the new development is actually based, they are not capable of acting as an element integrating the urban tissue themselves. Therefore, the approach focused on transport and traffic related goals is underlain by a wrong assumption as to their meaning in the life and functioning of cities. In the context of a purely scientific approach, the initial assumptions are wrong a priori. It needs to be acknowledged, however, that multimodal transport hubs and traffic junctions connected with efficiently functioning public transport can play such a role more effectively (Katowice, Gliwice railway station reconstruction project). Generating social, spatial, and economic benefits results largely from well and attractively designed public spaces, integrally bound with attractive functions of their envelopes.

A paradox of numerous linear elements in the city consists in the fact that they are perceived as elements which construct the city and deconstruct it at the same time. Undoubtedly, such elements include railways, roads, rivers, canals, and even uniform greenery belts. In this respect traffic routes and arteries constitute a big contemporary problem in Silesian cities. Without their intersections within the limits of the city or in its vicinity the life in the city would not exist at all, and the city would not be the space of exchange, as well as it would not be the destination of many travellers. The accessibility of the city would get reduced, too, and it is also its characteristic feature. The paradox, however, consists in the fact that at a certain stage traffic routes deconstruct the urban structure (examples of Katowice, Chorzów, Sosnowiec, Ruda Śląska, Zabrze). In this case the significance of transport leads to contradictory and inconsistent conclusions. Therefore, measures weakening the disintegrating role of transport seem to be extremely important. In the era of constantly growing volumes of public transport and cars moving around inner cities, this antinomy, or contradiction of the city's right to develop, will increase.

Maintaining the principles of continuity in space reduces the totalism of assumed forms and solutions. There occurs a certain feedback here, where continuity reduces totalism, and totalism interrupts continuity. Sometimes one has to set less ambitious aesthetic and design-related goals and to implement projects and facilities more adjusted to psychomotor capacities of an ordinary human being. At the beginning of the 19th century, Sebastian Sierakowski wrote: “For all centuries of greatness, the grandeur or shabbiness of a building was and is the measure

⁴ Numerous publications devoted to “transit oriented development” (TOD) are published on the website: [14].

of a magnificent or shabby mind” [13, p. 220]. The value of the preserved cultural heritage depends on the importance attached by the society to urban and architectural projects and to the process of shaping of the living environment, which each town and city is.

Good urban practice is more and more often mentioned in the Polish urban planning. Good practice is the practice that corresponds to human needs and possibilities. Unfortunately, everything that was destroyed in the last 70 years requires improvement and revitalisation. The role of an urban planner is extremely difficult in this respect. He is probably the only warden of spatial order in towns and cities.



Fig. 4. Fragmented, mosaic-like space of the centre of Katowice (photo by R. Blazy)

4. Effects of undertaken actions vs. Urban life

L. Mumford noticed that what transforms a village into a town is not merely the population density, nor access to specific resources, but everything that broadens the territory of mutual relations, which gives rise to a need of complex social cooperation, communication, and communion [10, pp. 5–7]. A characteristic feature of historic cities was the fact that a large portion of the urban life took place in streets and public spaces. Streets bustling with life are nearly synonymous with the city and urbanity; hence designing streets not connected with the urban life weakens the attractiveness and vitality of the city.

Population dynamics in communes of the province of Silesia in years 1999–2012 demonstrate that the largest outflows of people take place in the most central area of the

province and concern such communes as Katowice, Chorzów, Ruda Śląska, Zabrze, Piekary Śląskie, Świętochłowice, Gliwice, where a 5–10% drop of the total population was observed – the highest drop in this respect was registered in Bytom – 10%.

This is additionally strengthened by the migration of people from central areas of these cities to their suburbs. A considerable drop in this respect was recorded in Katowice. In the inner city of Katowice the number of permanent residents between 2008 and 2014 dropped nearly by ¼. At the same time, population density in the city centre dropped by ca. 1500 residents per square metre. Historically speaking, the area of the city centre used to be the most densely populated part of the city. Despite the fact that population density in the city centre is higher than in the areas adjacent to it (inner city districts), still their situation is much more stable as far as population is concerned. Studies confirm that a considerable drop in the number of permanent inhabitants of the inner city changes the way in which Katowice functions considerably.

Disintegration resulting from the drop in the population in city centres and downtown areas in Silesia consolidates negative effects of the new spatial organisation. Regress of palpable and non-abstract social relations has a very strong impact on the life of inner cities, as well as on the very physical form of cities. Weakening of physical relations between people, and even companies and other business entities, finds its reflection in the urban space. It is undoubtedly connected with the transfer of contacts, services and sales of goods to the virtual reality. The problem of human presence in the space of cities is not exclusively a transport-related problem, but a cultural one. The policy implemented in Barcelona, Copenhagen, or Helsinki can be quite interesting in this respect. It is a spatial policy oriented predominantly towards pedestrian traffic. In Barcelona, under relevant regulations of the municipal authorities, hypermarkets can be situated only in places easily accessible for pedestrians.

It seems that in our reality it is a factor which is completely disregarded. Demographic data of Silesian cities prove that we are still in the phase of deglomeration of inner cities, and populations of inner cities constantly drop, whereas suburbs expand. The population curve presented on the diagram (Fig. 5) illustrates tendencies occurring within the inner city of Katowice. This study is important as it illustrates what developmental phase we are currently in and what we can expect in the near future. Today, despite numerous revitalisations, inner cities do not get activated, because activities are limited only to the sphere of trade, and only to a certain extent to entertainment and other services. Outflow of people inhabiting city centres, confirmed in studies carried out by K. Bierwiazzonek and T. Nawrocki, as well as strongly competitive activities of shopping centres towards traditional city centres, seem to be the most significant in this respect. The constantly growing number of commuters accounts for the fact that many people who stay in the inner city even periodically, still behave in an alienated way, like “resilient aliens”.

The problem of functional transformations, necessary to be introduced in contemporary inner cities, is complex and multithreaded. Stopping the outflow of people inhabiting central districts seems to be essential in this respect. Municipal authorities should make efforts to constantly improve the attractiveness of the residential function in city centres and inner cities. This fact is firmly inscribed in the tradition of European cities, where city centres where inhabited by people from upper classes due to the accessibility of functions, as well as



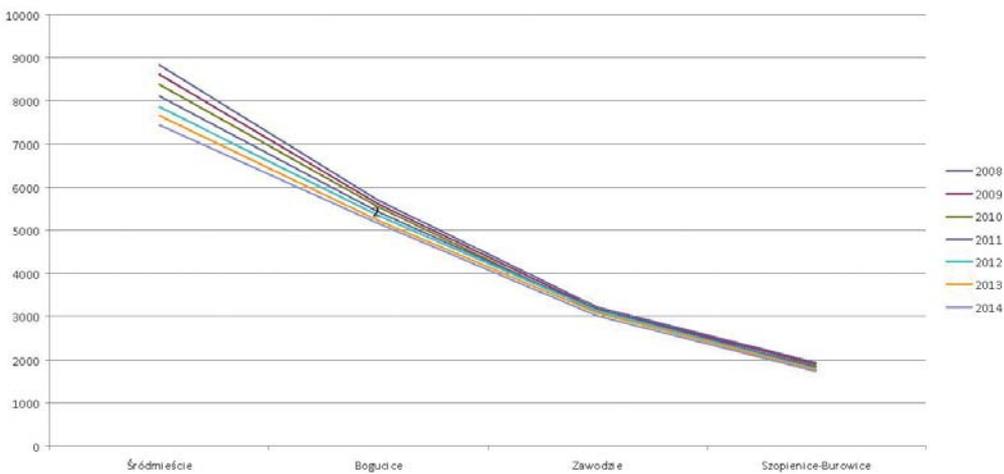
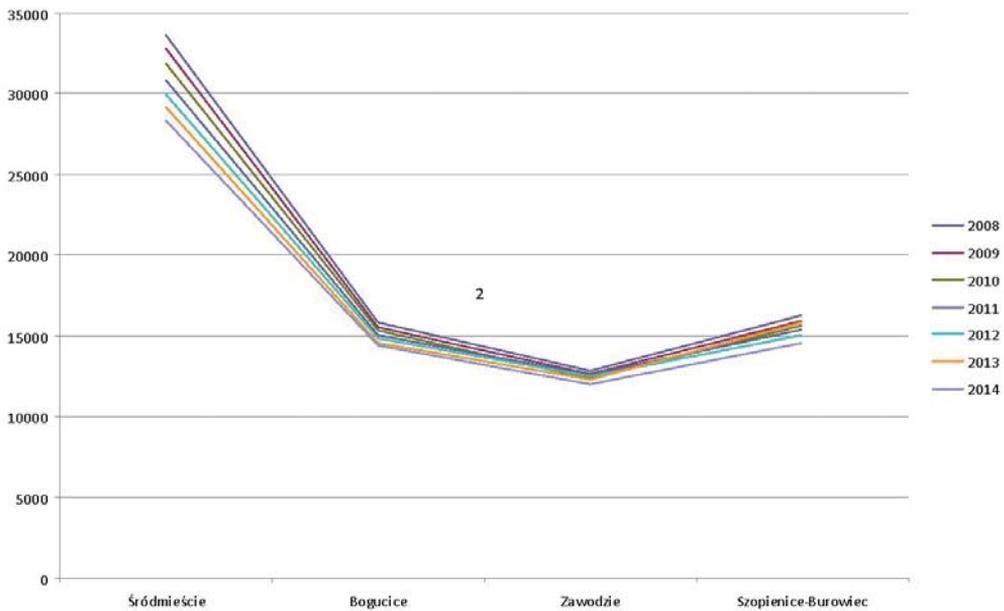
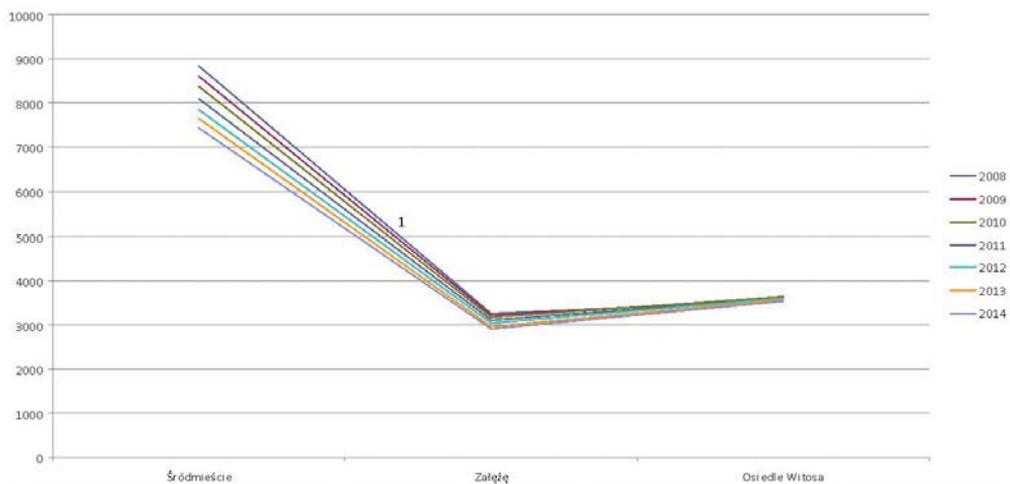
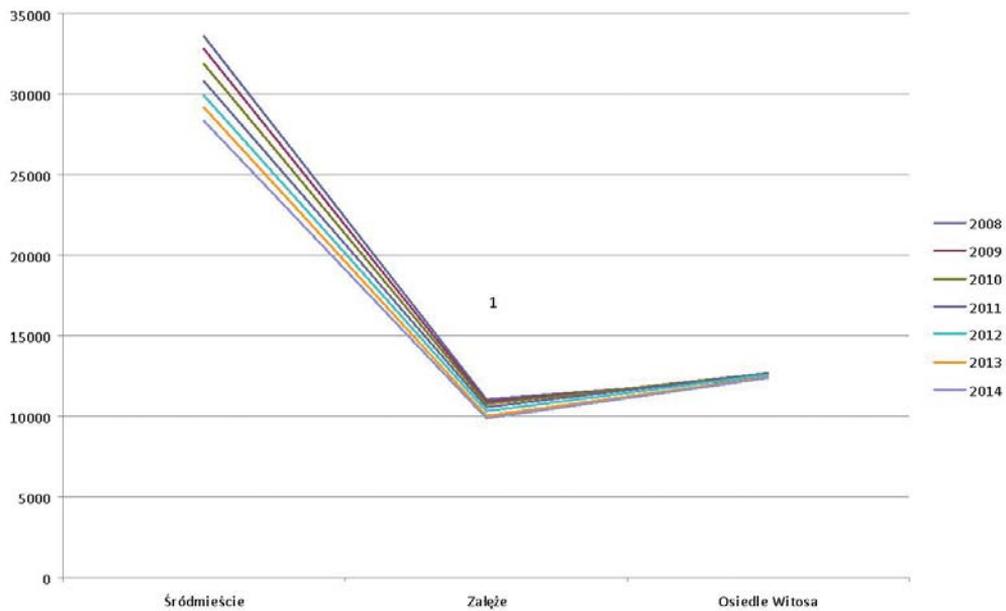


Fig. 5. Population and population density diagrams for selected central districts of Katowice (compiled by the Author on the basis of the data from the Katowice City Hall)



Cont. fig. 5. Population and population density diagrams for selected central districts of Katowice (compiled by the Author on the basis of the data from the Katowice City Hall)

prestige. Thus in numerous city centres on the so-called old continent we will find magnificent palaces, villas, residences, and hotels, very different in terms of form – as single edifices, as city blocks, or even as entire urban projects. Hence balancing and strengthening of the residential function in areas dominated by services and commerce should become a valid principle. It is crucial that commercial or business monostructures are not allowed in the city.

According to the CityLab portal, which refers to American studies, there is a growth of the demand for apartments in American inner cities today. It is connected with the so-called reduced tolerance for commuting to work, observed in households with a high double income. People who earn well usually spend more time in offices, and at the same time they long for free time. As the time allocated to rest shrinks, central locations become incredibly valuable as easily accessible areas. This fact becomes more and more significant as a very important factor taken into account when choosing a place of residence. The study was conducted on 27 cases of densely populated cities in the USA, where the total of 65 thousand locations (research points) were selected, subjected to observations lasting 30 years since 1980 until 2010. During this time a growing tendency in terms of preferences to live in city centres among highly qualified staff was observed. Simultaneously, researchers observed that highly qualified work is most concentrated in the very heart of the city. City centres (0–5 km) were inhabited by three times more highly qualified workers than inner cities (5–15 km); suburbs, on the other hand, were inhabited by seven times fewer highly qualified workers than in inner cities (15–30 km). These observations indicate that there is a tendency amongst hard-working well-educated inhabitants to live close to the city centre. American studies demonstrate what can be the actual dominating driving force in the increase of the attractiveness of the city centre as the place of residence and life [15].

Many times over centuries we have observed that the life of cities, as well as the life of people, is subjected to fluctuations; hence we can expect that quite soon a similar tendency might occur in the most important Silesian cities. Therefore, certain measures should be undertaken to meet the expectations observed globally.

5. Conclusions

When we wander around old districts of cities and admire their form and development, we face a very disturbing question of what is our current contribution in the history of building cities compared to grand works of urban planning and historic architecture. How will the future generations evaluate the legacy left by us? What facilities and structures must come into being so that this evaluation could be a positive one? Frequently we tend to evaluate positively structures whose construction is connected not only with satisfying the needs of their contemporary residents, but most of all with visionary concepts of their creators, who made a great effort to achieve their goal.

Most often common thinking on improving a city is limited to its structure, law, regulations, and institutions responsible for the city. When we adopt a historical approach, i.e. when we consider measures which brought about actual qualitative changes in the city, most often

they do not fall into the limits of the fixed legislative system, and therefore they required considerable efforts to be implemented. They did, however, bring very positive results, and very often became models for reconstructions of the urban structure.

The most important in this respect are changes in the social sphere relating to culture, ethics, mindset, and behaviour. They decide about the form of civilisation, its rhythms, and manifestations of life. Recognised individual models of life are decisive about the urban life. Human life cannot be regulated by regulations or structure, it cannot be done from the outside.

Space atomisation observed within the perimeter of Silesian cities takes place predominantly by means of free polarisation of priorities in spatial assumptions of new investments. Instead of compilation there occurs weakening, or even disintegration of existing functional links (example of Gliwice, Chorzów, and large areas of Katowice), which in turn contributes to the separation of the newly emerging function and form of development from the existing urban tissue, and eventually leads to erosion and fragmentation of the territory of the city.

At the end, it is worth quoting very accurate and important words of Barbara Bartkowicz:

One can and must [...] ask a question on the hierarchy of goals and the criteria of their selection. Irrespective of attitudes and differences of opinions of representatives of different fields of knowledge, the determinant and the superior criterion in the selection of goals and evaluation of actions should be human needs – not the current, present ones, but needs that are non-negotiable for maintaining humanity – physical and mental ones, which need to be satisfied in order to maintain good health and development of individuals as well as societies.

Without getting into details, it should be stated that deliberations of psychologists and sociologists point to the need to maintain balance in the selection of goals, as the primacy of e.g. economic or functional goals can jeopardise the ability to satisfy many other needs connected with the environment of human life (e.g. the need of peace, harmony, contact with nature, or sense of safety).

These premises of balance constitute the foundation for the general task of urban and spatial planning, which is creating harmonious spatial frameworks for comprehensive activities of individuals and societies in the pursuit of satisfying needs, self-actualisation, progress, and development. A confirmation, and at the same time formulation of this task is a broadly understood principle of sustainable development, underlying urban and spatial planning, which in the contemporary times have been defined in detail and adopted as applicable in all civilised parts of the world [1, pp. 9–10].

References

- [1] Bartkowicz B., *Cele i zasady w planowaniu przestrzennym i urbanistyce a projekty unijne w Małopolsce*, Czasopismo Techniczne, 15-A/2005, 9–10.
- [2] Bartkowicz B., *Ewolucja poglądów od strefy ochrony do równoważenia rozwoju struktury miejskiej ze szczególnym uwzględnieniem projektów dla Tarnowa*, Czasopismo Techniczne, 7-A/2007, 21–34.
- [3] Bartkowicz B., *Problemy harmonizowania przestrzeni Polskich miast i obszarów w świetle wewnętrznych uwarunkowań oraz integracji z Unią Europejską*, Czasopismo Techniczne 2-A/2005, 28–35.
- [4] Bartkowicz B., *Ustalenia planów zagospodarowania przestrzennego w świetle zmieniających się przepisów prawa a oczekiwania odbiorców*, [in:] *Skuteczność planów zagospodarowania przestrzennego potrzeby i możliwości*, Kraków 2003.



- [5] Bierwiaczonek K., Nawrocki T., *Centrum miasta czy mall? Kilka refleksji socjologów na marginesie badań przestrzeni publicznych miast śląskich*, Górnos Śląskie Studia Socjologiczne, Seria Nowa 2, 213–231.
- [6] Gasidło K., *Kierunki przekształceń przestrzeni przemysłu*, Publishing House of the Silesian University of Technology, Monograph, Vol. 269, Gliwice 2010.
- [7] Jałowiecki B., *Człowiek w przestrzeni miasta*, Katowice 1980.
- [8] Jałowiecki B., *Przestrzeń ludyczna – nowe obszary metropolii*, Studia Regionalne i Lokalne, No. 3(21), 2005.
- [9] Jałowiecki B., *Znaczenie przestrzeni*, Studia Socjologiczne, No. ½, 1991.
- [10] Mumford L., *Miasto*, Polis, No. 6, 1996.
- [11] Nawrocki T., *Miasto bez centrum? Centrum Katowic w oczach mieszkańców*, [in:] *Przemiany miasta. Wokół socjologii Aleksandra Wallisa*, ed. B. Jałowiecki, A. Majer, M.S. Szczepański, Scholar, Warszawa 2005.
- [12] Nawrocki T., *Koszmar sen. Centrum przemysłowych Katowic w oczach mieszkańców*, Przegląd Socjologiczny, Vol. 57, No. 1, 2008, 249–269.
- [13] Sierakowski S., *Architektura obejmująca wszelki gatunek murowania i budowania*, Drukarnia Akademicka, Vol. 1, Kraków 1812.
- [14] [http://www.nlc.org/program-initiative/sustainable-cities-institute/topics/land-use-and-planning/transit-oriented-development-\(tod\)](http://www.nlc.org/program-initiative/sustainable-cities-institute/topics/land-use-and-planning/transit-oriented-development-(tod)) (access: 31.01.2018).
- [15] <https://www.citylab.com/transportation/2015/11/why-the-wealthy-have-been-returning-to-the-city-center/416397> (access: 31.01.2018).
- [16] <http://www.mck.katowice.eu> (access: 31.01.2018).
- [17] <http://www.nospr.org.pl/pl/o-projekcie> (access: 31.01.2018).
- [18] <http://www.urbanity.pl/slaskie/katowice> (access: 31.01.2018).
- [19] http://katowice.wyborcza.pl/katowice/1,35063,13517913,7_03_2000_r___Centrum_Sosnowca___czyli_jeden_wielki.html (access: 31.01.2018).
- [20] <http://www.nowiny.gliwice.pl/centrum-przesiadkowe-w-gliwicach-ma-powstac-za-trzy-lata> (access: 31.01.2018).

ADDENDUM

Examples of big investments relating to reconstructions of Silesian city centres.

International Conference Centre (near Spodek)

Implementation: since 2011 until March 2015.

Total value of the project: PLN 378 million [16]

National Polish Radio Symphony Orchestra Katowice

Implementation: December 2010–October 2014

Total cost: PLN 305 million [17]

Silesia Business Park

Commencement – June 2013

Completion – September 2018 [18]

KTW Katowice

Commencement - June 2016

Completion – June 2018 [18]

Silesia Shopping Centre

Commencement – 2004

Completion – November 2005

Reconstruction 1 – September 2010–2011 [18]

Katowice Railway Station and Gallery: Integrated Transport – Commerce – Office Centre

Commencement – 2010

Completion – 2014

Total cost of the project is estimated at PLN 1056 million [18]

Agora Bytom

Commencement – March 2009

Completion – November 2010

Total value of the investment is PLN 186 million [18]

Reconstruction of the city centre of Sosnowiec 2002

Reconstruction in 2002 comprised the railway station and Stulecia square

Railway station – 1997–2002

The renovation of the railway station cost PLN 26 million [18]

Stulecia square – PLN 95 million [19]

Gliwice Transport Hub. Designed by An Archi Group

Commencement – autumn 2018

Completion – 2020

Cost of the investment ca. PLN 150 million [20]

Marcin Charciarek (marcincharciarek@op.pl)
Institute of Architectural Design, Faculty of Architecture, Cracow a University of Technology

FORMS, DETAILS AND CONTEMPORARY MEANINGS
OF POLISH CONCRETE ARCHITECTURE, PART I

FORMY, DETALE I WSPÓŁCZESNE ZNACZENIA
POLSKIEJ ARCHITEKTURY BETONOWEJ, CZĘŚĆ I

Abstract

The article is an attempt to show the relationship between architectural ideas and concrete matter in the implementation of Polish architecture of the beginning of the 21st century. The first part shows examples in which the perfection of architecture is associated not only with the rational principles of 20th century architecture, but also with what we define as the search for aesthetics in appropriate expression of forms.

Keywords: concrete architecture, idea, matter, expressionisme

Streszczenie

Artykuł podejmuje próbę przedstawienia związku między ideami architektonicznymi a betonem jako materią w tworzeniu polskiej architektury na początku XXI wieku. Pierwsza część przedstawia przykłady, w których doskonałość architektury postrzegana jest nie tylko w odwołaniu do racjonalizmu architektury XX wieku, lecz także w związku z tym, co można by zdefiniować jako poszukiwanie estetyki w odpowiednich formach wyrazu.

Słowa kluczowe: architektura betonowa, idea, materiał, ekspresjonizm

1. Concrete architecture

Concrete narrations in contemporary architecture are not explicit. It could be said that concrete and its forms cause extreme emotions and aesthetic reactions. Within one century, the myth of modern material, which helped to build a “new world”, has been discredited by an image of something ugly, imperfect and boring. However, nowadays, this novelty and “non-explicitness” have become one of the most significant features describing concrete. The mixture of water, cement and aggregate has become “the philosopher’s stone”, which can transform a murky mass into a material revealing further meanings and stylistic senses of architecture.

A fundamental metaphor of concrete is established and partly derives from the specifics of a visual code and its meanings – concrete imitates stone – it may have its optical, tactile and technical qualities. The unity of stone and concrete was defined at the beginning of the 20th century by Auguste Perret, who was first to compare concrete to “a rejuvenated stone” [*Pierre rejeuni*]. The metaphor was discovered and spread by Le Corbusier after building his Unité d’Habitation where concrete adopted the qualities of a natural rock. Le Corbusier claimed, “concrete is a recreated/reconstructed stone, worth exhibiting in its natural state”. Another great modernist Louis Kahn, while building The Salk Institute, defined concrete as a *liquid stone* or a *hollow stone*. A material that takes over all constitutive qualities of a stone – hardness/firmness, texture, poetics, symbolism and mythology.

Nowadays, a lot of architects still think of concrete as “a contemporary stone”, “a matter without the defects of stone”. Concrete is still a means of conveying various architectural ideas and is a quintessence of materiality – it is a material whose secret is revealed in technical and technological knowledge, in a “mystery” discovered by a logical and scientific act. For an architect, concrete becomes an end in itself – he creates concrete in his imagination, from the need to show the form and meaning of its physical and aesthetic qualities. The choice of material goes hand in hand with the choice of technique. Formwork appears as a matrix for a form that acts as a “positive” of an architect’s imagination. What is more, concrete is “loaded” not only with energy, laws or potential, but also with diverse ways of artistic and pre-artistic creation.

Nevertheless, concrete as a building material does not exist independently. Frank Lloyd Wright called concrete a stone created *in form*. Therefore, concrete is a form of formwork – a form assumed in the mind of a creator, which gives architecture its aesthetic and technical sense. Cyrille Simonnet describes concrete as a state of matter *without an original image* [1, pp. 55–75], which among other materials – due to its “liquid” nature – has no model, no original form that could be demonstrated through reproduction/copying. Produced as the result of a chemical, technical or aesthetic thought, concrete and reinforced concrete are always related to the state whose definition and image never seem to be completed and closed.

Due to its potential for transformation, concrete seems to be the “matrix” of architectural ideas – concrete is a material trace “prone to imagining” and an imprint of formal expressions. As an unbound, composite matter (a mixture of aggregate, water and cement), concrete is – to a certain extent – a synonym to Aristotle’s “prime matter”, which could be treated as a metaphysical substrate of changes in architecture. Primarily, concrete is only a name, a quality which has the ability of taking shapes – it is a universal body. As a ready substance, frozen in

form, concrete becomes a “secondary matter” – a *material* whose physical qualities become a building material for an idea/metaphor defined by a creator. These two categories of matter are the proper subject of an architect’s work – as a physical object, as a “substrate” – a basis for any architectural forms, but also as an “abstract” – showing its qualities and meanings given by an architect.

In both states of aggregation, concrete “gains the privilege” of becoming a metaphor – a transgression of qualities creating new, unique meanings of architecture. Concrete, together with its “elusive” nature, becomes rather an element than a body or substance, in the same sense as fire, water, air and earth. Louis Kahn emphasised this aspect of concrete by appealing to the common sense and intuition of architects: “You must know the nature of concrete, that what it really wants to be. Concrete wants to be granite, but it will never become it. Iron rods might act as a secret creator enabling this so-called liquid stone to appear as a splendid creation of the human mind. [...] That is what concrete wants to be: a product of a mind” [2, pp. 26–33].

Concrete architecture is an example of creation, where a creator makes ideal and formal decisions based on *a priori* chosen building material. Concrete architecture is a discipline where everything designed by a creator is totally submitted to concrete. Similarly to a sculptor, whose work totally depends on matter, an architect first looks for a material, and only then decides about the shape “hidden” in the material. Unlike steel, brick or wood, concrete is ideally predestined to this role because concrete itself is a matter *in statu nascendi*, gaining sense and changing meanings with the change of an ideal or formal context. This aesthetic “effectiveness” of concrete is a quality subordinated to the creator’s will to show some general content where concrete acts as a fundament, as well as more detailed solutions where concrete conveys the essence of its usage.

2. Detail

For the last one hundred years, a concrete detail has been this place where architects building from concrete have tried to find a specific “nature” of concrete buildings. It does not matter what we are looking at – a modern, post-modern or deconstructionist building – an architectural detail seems to have the same potential as the whole structure/building. In the search for formal models of architecture, we reach the moment when we begin to understand that a concrete detail also has its model references – hidden in fully conscious and determined acts of an architect. This analogical rule can be seen in “stark, concrete” buildings by August Perret and Le Corbusier, in decorative stylistics of Carlo Scarpa or in Louis Kahn’s detail “finding order”. Each of them created different basis for the understanding and logic of the architectural detail – regardless of the fact if it is an autonomic part of architecture or it is treated as its completion.

Although stylistic aspirations vary, the clarity and ideal honesty seem to be the same for all of them. Perret looked to the past, to a classic gothic cathedral. For Le Corbusier, his vision of an ideal detail was, at the same time, thinking *from general to detail* and *from detail to general* and the balance between those two poles of architecture. After years of technical solutions, Le Corbusier’s “narrative detail” [*detail parlant*] inspired by an orphic motif (mainly male–



female) was transformed into the principle of architectural image/picture hidden in a detail reproducing the unity of an idea and a material. For Carlo Scarpa, a detail is this category of architecture that derives from individual beauty – “a beautiful detail” or “beautiful parts”, which connected into a whole become *ideal* beauty.

According to Louis Kahn, the detail is the very beginning of any architecture – “if you deal with a fragment, regardless its size, structure, light, you react to its character, its spiritual atmosphere. We notice that everything proposed and realised by a man becomes an individual being” [3, p. 69]. Kenneth Frampton shares this opinion. He treats detail as an essential part of a joint that gives a relevant, narrative meaning to every structure through the visibility and quality of the joints: “Constructing and interpreting architecture happens in a joint, in a fertile detail. [...] The original Indo-European core of the word art means joint” [4, p. 18]. The principle of transgression and joint does not only reflect a system of building, but it also “designates” joint connections for the whole structure. This type of thinking results in discussions about what once was called an ornament and now is called an architectonic detail.

Nowadays, in Poland, there are a few architects who follow the abovementioned. They associate perfection of architecture with something, which we define as the search for aesthetics in an adequate expression of forms. For some of them, due to its qualities, concrete becomes a thing that belongs to the world beyond architecture – in keeping Le Corbusier’s thesis that “architecture is a plastic problem”. This poetic transformation of concrete into an image becomes an inherent attribute of expressive metaphors. For others, architecture is an opportunity to demonstrate/show order through a building material – simple and honest in its message – corresponding to Le Corbusier’s symbol of “an open hand”. For them, concrete becomes the tool for creating a rational space supported by a reduction of means of expression.

Does concrete in recent Polish architecture have these two different faces? It seems that both stylistics of concrete architecture are clear and create in their own ways a coherent world filled with architects’ convictions about the perfection of the used material. Also, both ways of presentation – metaphoric and rational - should not be treated as opposition, but as a competition for contemporary forms. A detail of concrete architecture creates new typologies and emphasises its own unique style.

3. Looking for expression – metaphors in concrete

In architecture, the image of reality has always seemed “insufficient” and it might be the reason for creating metaphoric architecture that has “compensating” functions. Once, it is a belief in a poetic need to use the power of metaphor to enhance the formal expression of a building. Another time, it is the awareness of architecture as publicly received art, which is the reason of introducing architecture into the world of unusual communication with a viewer through the language of fiction – things emphasising freedom of expression against normalised reality. This poetic interpretation of architecture as the art of creating “new” is a metaphoric image – it gains its own individual value and a proper semantic status.



Fig. 1. F. Menis, Jordanki Cultural Congress Centre in Toruń (2015). Detail of *picado*



The constant emphasis of isotopic qualities of concrete is characteristic for Fernando Menis. **Jordanki Cultural Congress Centre in Toruń** (2015; Fig. 1) and is an example of looking for such stone qualities of concrete, which would be adequate to reinterpret architecture as a thing based on the archetype of the cave (also the grave, shelter, bunker, bastion). The cave is a principle of creating a stereotomic space – mass subtracted in matter, connected with earth or rock – it introduces us to the world of mass, darkness, emptiness and mystery, separation from the outside world. It is stability and connection with the basis. Menis likes stark architectural forms relating to the shapes of nature. He mainly uses concrete, wood and stone juxtaposing their colours and textures and bringing out the qualities of their structure by the play of light and shade.

In the monumental Toruń building, a detail attained a very specific identification. From the outside, the block is made from light concrete with a visible sketch of wooden boarding divided into diagonal squares, which introduce a sense of dynamism that emphasises a strong organic form. Carvings, overhangs and shelves in intensive colours attract our attention. *Picado*, which is concrete mixed with brick, is a conscious reference to the historic brick buildings of Toruń. This interesting conglomeration of concrete and aggregate highlights the dichotomy between heritage and modernity in the cultural centre. Inside the building, the sculpted surface of the concert hall is accompanied by rooms that remind labyrinths and flexibly connect various functions. In Jordanki Centre, concrete through its monolithic representation fulfils the sense of *topophilia* – the subjective and emotional reception of the place and its material character.

In the concert hall, *picado* gains a new additional meaning. Apart from plastic effects, concrete is a matter that absorbs sounds. Due to the use of mobile ceilings and other technically advanced solutions, *picado* has excellent acoustics and acts as an absorber during symphonic concerts and opera performances. All in all, the mixture used by the architect gave the building a mimetic character in relation to the historic centre of Toruń. What is more, it also got a function of solid protection/wall separating this space from the surrounding noise of the city. Three independent concrete volumes determine darkness and silence of the space where the simplicity and starkness of the material are accompanied by light going through the cuts in porous cubatures. Together with the lighting, concrete refers to the walls of Plato's cave, which reflect the unreality of the real world. Shattered and diffused light creates fantastical patterns and figures. Their interpretation depends on the perspective, knowledge and sensitivity of the viewer. The understanding of this idea depends on the shape of an image projected "onto" the matter and transformed "into" matter. And if it is true that "the sensual world is older than the rational world" [5, p. 205], the astonishment towards matter and lit spatial shapes ordered in matter is an excuse to discover the architecture of Fernando Menis. The metaphor of such building reveals a real fundamental base for this part of architecture where searching for sense consists in finding material meanings.

We can see a similar role of concrete – relevant for transforming the concept of a concert hall into a real image of architecture – in the building designed by Konior Studio for **The National Symphonic Orchestra of The Polish Radio** in Katowice (2014; Fig. 2). The concert hall was treated as a monolithic "vessel for sounds". The metaphor of a vessel is an

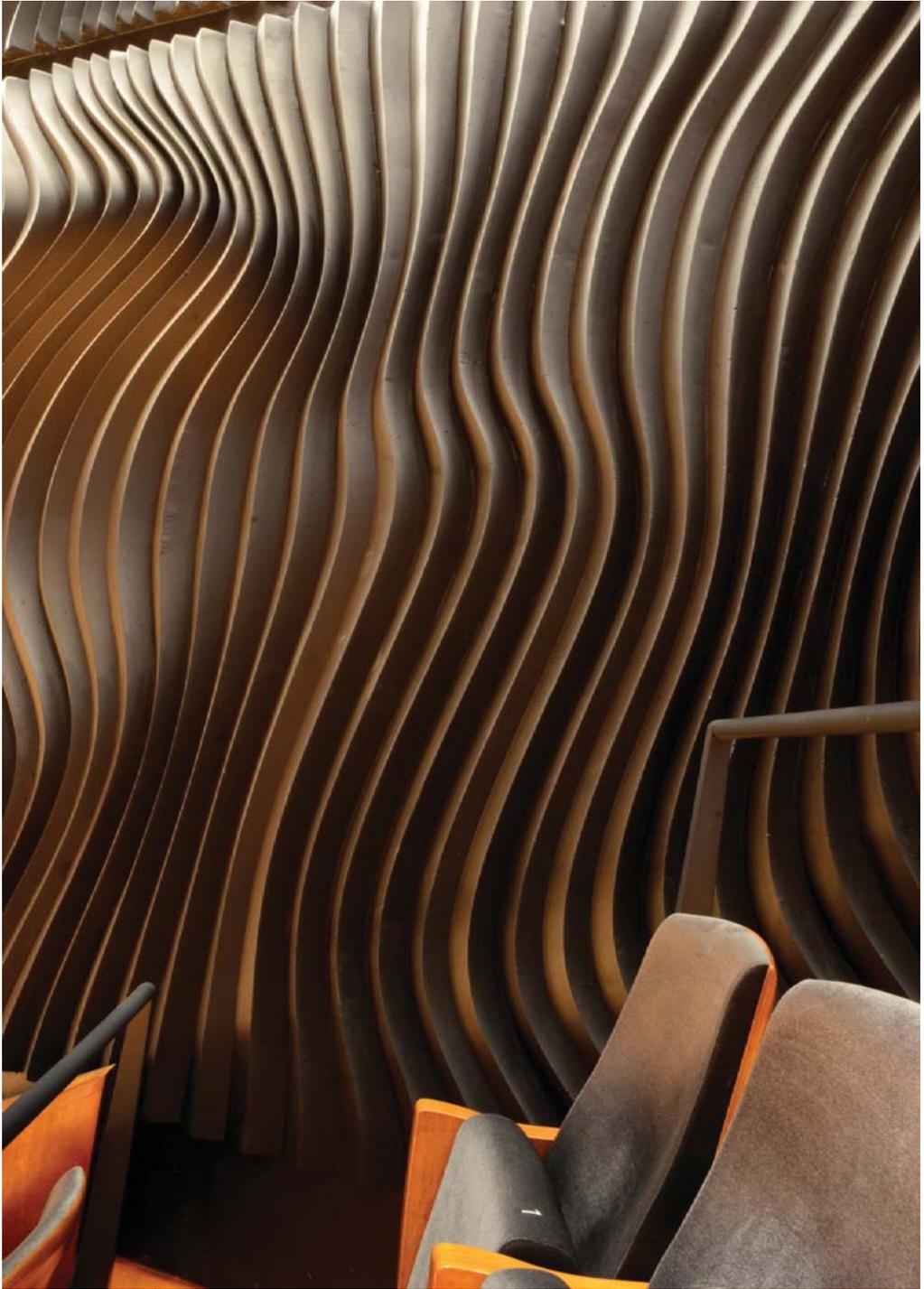


Fig. 2. Konior Studio, The National Symphonic Orchestra of The Polish Radio in Katowice, 2014.
Wall of Concert Hall



excellent depiction of adequate formation in adequate matter in order to transfer this or another imagined content. Form, content and material should become one, they should complete each other. The way of designing and building NSOPR reveals a creative sensuality, a perception and reception of form and selecting adequate materials – they also prove the architect's praise of patience in creating detail. The NSOPR building is the praise of a specific process of forming a building. Systematic buildings from concrete and brick, together with the sensitivity to light, touch, hearing, come from a deep belief that architecture is a certain "slowness" of acting, aspiring to perfection, but also – eventually – a feeling of immaterial aura created by material objects. In such approach, we can recognise a reference to Louis Kahn's statement that a building must begin with the *immeasurable*, it must go through being designed and built in order to re – present its *immateriality*. When we look at the NSOPR building, we should appreciate a visible care about the quality of each element – it might be the texture of the anthracite overhang bearing the traces of boarding in the foyer, intricately impressed relieves on the walls of the main concert hall or the hand-baked facade brick. The architect was able to turn concrete matter into a form that emphasises the weight and density of "liquid stone" and shows its plastic and liquid potential – the space transforms from a hefty, impervious concert hall into a sophisticated play of concrete wall folds. Each detail completes the form to create a sense of *Gesamtkunstwerk*, where form should be interpreted as a structure of space and matter, regardless of being represented in equilibrium of blocks or the alternation of light and shade. In Tomasz Konior's version of architecture, there are two equally important aspects: the understanding of concrete matter and the determination to transform "a usual object" into "a unique object".

Another model example showing the connection between the city's physiognomy and the contemporary concrete architecture is **The Museum of The Second World War in Gdańsk** (2016; Fig. 3), designed by the local Studio Kwadrat. The characteristic red building with a dominant 40-metre high tower is situated on the bank of Radunia. The building is not only a mere symbol of the city; not only does it include connotations with the silhouette of Gdańsk Old Town, but it also defines a certain range of comparisons. In its open to interpretation shape, the museum follows the tradition of creating contemporary architectonic forms that should express, not only represent. The expressionist design of the building refers to the specific historic and political values avoiding symbolic solutions. A decomposed form, together with its sophisticated geometry, seems to be a manifesto for discussing the Second World War. According to the designers, it is supposed to be "a universal sign", a tribute to the successful attempt of translating the stability of matter into "the energy of form". The building, which looks like a leaning prism, might bring associations with a missile or a house damaged during a war. The abstract form does not imitate any known shapes. Therefore, instead of simple reproduction, it creates a disturbing atmosphere of the place. Some see it as a sinking ship, some compare it to a crumbling building while others see it as a rocket half-buried in the ground, a dam, an obstacle or a grave candle.

The main material of the building – monolithic concrete, is invisible to the viewer. It is covered with irregularly put facing from red *torkrete* and facade glass. Yet it is concrete that is responsible for creating "a wobbly" space whose material coherence allows to interpret the multi-layered shape and superior spatial logic. Inside, the homogeneity of red planes gives place to a homogeneous

stark monolith completed with anthracite panels, exposed installations and simple wooden furniture. All of it gives us the specific meaning of war monuments – shelters, bunkers, redoubts. By creating a whole, concrete announces the eccentricity of the building-sculpture and the designers' uncompromising approach to form – the function of the building seems secondary.

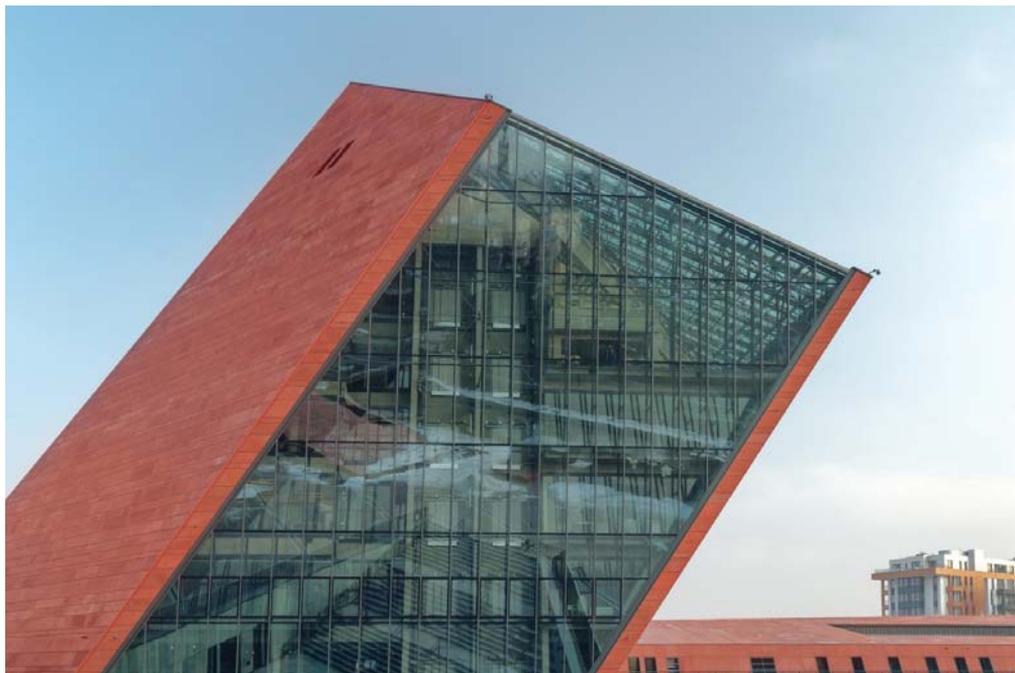


Fig. 3. Kwadrat Studio, The Museum of The Second World War in Gdańsk, 2014

Aerotunnel in Mory near Warsaw (2014; Fig. 4), designed by Lewicki and Latak Studio, also has theoretical references. This unusually shaped tower is a place where you can learn parachute jumping and experience the sheer joy of being torn from the ground. According to the designers, the unusual shape was inspired by a plastic bag filled with air. The bag takes on irregular and unpredictable shapes. A bag, a kite, a sleeve, a paper balloon are forms we always associate with first attempts of taking off, flying and counteracting gravity. A very special problem in the case of this object was the right choice of material. After all, the designers' ambition was to show the struggle between wind and gravity. At first, they thought of a technical fabric, but finally they decided on reinforced concrete. Reinforced concrete allowed them to introduce additional functions. It also allowed a stable wind flow. This expressive form (very closely resembling *The Einstein Observatory* in Potsdam, by Erich Mendelsohn, 1921) has the features of an interesting deconstruction. For a modern architect, a function is not the only reason to create, the reason to create is rather a concept supported by imagination. The aim of imagination is to find the most original shape for a building in a chosen material. The world of dynamic and radically decomposed architecture tells us that architecture cannot survive without concrete. Even the most extreme independence of form

assumes an adequate matter in which the form will be revealed. In the *Aerotunnel*, naturally cast concrete in a system formwork becomes a dynamic material supporting the sense of shape “frozen in one pose” and creating a kaleidoscopic play of light, shade, asymmetry as well as the imagination of the designers.

The building of **The Museum of Polish Aviation in Kraków** (2010; Fig. 5) required a specific approach to concrete (designed by Pysall, Ruge Architekten and Bartłomiej Kisielewski). The building attracts attention due to a careful layout clearly associated with the function of the museum and the presented exhibits. The basis for the museum shape is a modification of a basic module, which looks like a cut and folded (like origami) square sheet of paper resembling in its layout a triangular propeller. Based on a concrete platform, massive cement pliability/litheness and ubiquitous “supremacy” of concrete planes recreate a certain sense in interpreting form for function. The aspect of freedom of composition seems to follow ideas shared by Oscar Niemeyer, Eero Saarinen, Frank Gehry and Zaha Hadid. It manifests the sense of an architectural sculpture to show other sculptures/exhibits; to create a *work of art for other works of art*. Thanks to them, we know that a curved line, a curved plane, an arched substring are natural shapes of architecture. The aesthetic values of a building can be expressed only through idiopathic components.

This sophisticated metaphor rejecting a right angle and its unhindered geometry is accompanied by a visible care about each concrete, steel or glass detail. The curves of the outside 120-centimetre shell made from dyed anthracite concrete required special solutions and profiled lost formwork put on a steel substructure. The repetitive trace of impressed formwork tops, the finishing touch of corners, windows, the interior of museum rooms and offices, or the final polishing of facades prove that the detail separated from the fundament of modernist myth becomes an important freed from low quality element – it depends on the vision, sensitivity and knowledge of those who re-create it again and again.

The Museum of Martyrdom of Polish Country Folk (designed by Nizio Design International, 2017; Fig. 6) in Michniów belongs to another category of deconstructed concrete metaphors. It commemorates the tragic pacification of the village by the Nazis in July 1943. The architecture of the building is connected with recognisable archetypes of: The House, the Way, the Gate, the Border, the Garden, the Tree. Some of these elements are repetitive and recognisable – other create the world subordinated to the materialisation of ideas through preservation in the material. Together, all of them create the model where light, water, building material are as important as its specific formal shape.

The design of the museum is a consistent continuation of the concept aiming to show the disintegration and deformation of a traditional country house. The linear monumental figure emphasises the unity of historic and architectonic narration. Its main sense is the monolith of concrete. The road you have to follow through cement walls tells us about the tragic events. It also builds additional narration. Starting from the full figure of the “House” (serving as a chapel), through individual scattered parts of the exposition, eventually we reach the place that determines the final disappearance and destruction. Light shining through windows and skylights in an 80-centimeter outside wall is an essential element of this symbolic road. The stripes of light, together with inner facades, create a consistent composition of lines,



Fig. 4. Lewicki and Latak Studio, Aerotunnel in Mory, 2014



Fig. 5. Pysall, Ruge Architekten and Bartłomiej Kisielewski, The Museum of Polish Aviation in Kraków, 2010



cuts and rays adequate for the object that should transform profane matter in sacred space commemorating the tragedy of the people from Michniów.

The symbolism of “non-presence”, through a “naked” and impersonal form frozen in concrete, becomes a fundamental image after a non-existing object. By using the essential, well-known metaphor of the house, the designers create the universal sign of disintegration, death and passing based on the dualism of something that is present and non-present at the same time. Concrete “houses” in Michniów seem to visualise a “post mortem mask of architecture”.



Fig. 6. Nizio Design, The Museum of Martyrdom of Polish Country Folk, Michniów 2017

References

- [1] Simonnet C., *Le Béton en représentation – La Mémoire photographique de l'entreprise Hennebique 1890–1930*, Paris 1993, 55–75.
- [2] McCarter R., *Louis Kahn and Nature of Concrete*, “Concrete International” (32) 12, Farmington Hills 2009, 26–33.
- [3] Brownlee D.B., *Carnet du visiteur: Louis I. Kahn, le monde de l'architecte*, Paris 1992.
- [4] Frampton K., *Rappel à l'ordre; Głos w sprawie tektoniki*, Czasopismo Techniczne, 14-A/2011.
- [5] Merleau-Ponty M., *Oko i umysł. Szkice o malarstwie*, Gdańsk 1996.

Marcin Charciarek (marcincharciarek@op.pl)
Institute of Architectural Design, Faculty of Architecture, Cracow University of Technology

FORMS, DETAILS AND CONTEMPORARY MEANINGS
OF POLISH CONCRETE ARCHITECTURE, PART 2

FORMY, DETALE I WSPÓŁCZESNE ZNACZENIA
POLSKIEJ ARCHITEKTURY BETONOWEJ, CZĘŚĆ 2

Abstract

The article is an attempt to show the relationship between architectural ideas and concrete matter in the implementation of Polish architecture of the beginning of the 21st century. The second part shows examples in which the perfection of architecture is associated not only with the metaphor principles of 20th century architecture, but also with what we define as the search for aesthetics in appropriate geometry of forms.

Keywords: concrete architecture, idea, matter, expressionism

Streszczenie

Artykuł podejmuje próbę przedstawienia związku między ideami architektonicznymi a betonem jako materia w tworzeniu polskiej architektury początku XXI wieku. Druga część przedstawia przykłady, w których doskonałość architektury postrzegana jest nie tylko w odwołaniu do metaforycznych podstaw architektury XX wieku, lecz także w związku z tym, co można by zdefiniować jako poszukiwanie estetyki w odpowiedniej geometrii form.

Słowa kluczowe: architektura betonowa, idea, materiał, ekspresjonizm

1. Searching for perfection – rational concrete

One hundred years ago, Adolf Loos talked about the ruling “barbaric splendour”. This statement revealed a deeply rooted belief that modern architects had different standards of perfection. In the history of Western art, there is another aesthetic idea – the idea of aesthetic restraint, which is strictly connected with a classical tradition. According to Ernst Gombrich, a purposeful rejection of too many ornaments always pointed to the classical influence. When it became a point of pride as in the times of the Italian Renaissance or the 18th century Neoclassicism, focusing on form rather than on decoration was the sign of the self-aware artistic virtue [1, p. 18]. Such understanding of rationalism gives us the explicit answer to the question about the participation and sense of architectural detail in creating meanings of *elementary architecture*. According to this principle, architecture should be self-describing and introvert. Thus, a language used by a designer should strictly derive from logic, simplicity, geometry and numbers – from technique. Rational architecture without a distinguished detail should point to a difference between this which is “inside” and this which is “outside”. Architecture “outside style” is the main formal function for architects searching for objective beauty. For the architects who repeat that “an architect does not create anything, an architect only transforms reality” the honesty of matter eliminates this which is unnecessary, but it also searches for sense in this which we call continuation.

“Rational concrete” as an obvious part of contemporary landscape has become, through its naturalness, neutrality, syntheticity, an ideal material for architects who believe in formal reduction. It is the matter produced by an anonymous technique. It is the matter of things that do not have consolidated meaningful and aesthetic references. Concrete as matter suited for stylistic reductions finds its sources in aesthetics that becomes impersonal and devoid of references. As *non-imitating, non-shocking, non-present material* concrete is a perfect material to deprive art from the possibility of analysing the way of creation.

Robert Konieczny’s own house in Brenna in Beskid Śląski, built in 2015 (Fig. 1), is close to the idea of formal reduction. The building shows one more meaning of “the house” form whose architectural expression is reduced to the geometric essence of the archetype (the architect calls it “**the Ark**”). The concrete object is situated on a slope. Although it was built as the result of matching to geological and legal conditions, it is exceptional in its approach to form incorporated in concrete. In the architecture of the Ark, the standardisation and simplification of form become a purpose, where reduction is understood as the function of the simplest solution. The house has a gabled roof, a foundation analogical to the roof, four walls, a panoramic window, an entrance. Everything is bound by a pure greyness of monolithic concrete and carefully performed roof without chimneys. The succinctness of the house resembles Christian Kerez’s chapel in Cazis (1993) where the simple rhetoric of architecture reaches the moment when a reference to minimalistic means defines calculations: what and how many elements are needed to build an architectural object. It seems that for a purist such as Konieczny, “a physical” approach to an object is superior towards the idea of the object. The architect reduces to the minimum its artistic value, reduced cannon of succinct forms –



Fig. 1. Robert Konieczny, KWK Promes, *The Ark*, Brenna 2015



such as a rectangle, a triangle, a plane, an edge. He consciously gives up giving quality to the structures of a surface – he gives up everything that can define unnecessary and additional narration of architecture. Konieczny’s “neutral concrete” is a process of transposition of the ideal material for the “architecture of simplicity” where nature and geometry do not ask about the content, but about the methods defining elementary space.

The house designed by DB2, Iwona Wilczek and Mariusz Tenczyński team and built in Bierkowice near Opole (2015; Fig. 2) is an uncompromised and explicit explanation of what is a contemporary living space. A 452-m² building is a carefully designed structure cast in raw concrete and completed with a system of glazing opened to the inner part of the plot. This rectangular block reveals to us its double face – its border is a monolithic wall demarcating the entrance part (with a concrete square) from the living part whose open plan, together with ordered corridors and openings, is a counterpoint for a solid north-eastern facade. The unsophisticated and simple concrete of the entrance does not hide its own nature. Its imperfection creates the sense of a very simple and regular thing whose elementary function is to build a space of silence, wealth and privacy hidden behind an impenetrable wall. The entrance to the house outlines the way through a clear composition of blocks, planes, facing and furniture framed by the concrete overhang. All of it is surrounded by a pool and defines a complete composition.

The inventiveness of this building consists in a consistent and rational way of achieving the shape of architecture. For the designers, “discover” means “to find again”, “to re-order” this



Fig. 2. Studio DB2, *House in Bierkowice*, 2015

which is hidden in a creative subconsciousness and which finally means the abstracting of architecture towards Euclidean geometry that is pure and full of references. This compositional rigor is a manifest of reducing form to its essence or creating the ideal. For a rationalist, such “need of creation” is also “a need of form” where balance between the most important elements is a dominant feature. The idealisation of form in the house near Opole is searching for this body, which would be able to “reveal the soul” of the neat concrete-glass architecture.

The Gate of Poznań – the **Interactive Centre of the History of Ostrów Tumski** (Ad Artis Architects, 2014; Fig. 3) is an example of revealing the universal laws of geometry. The object’s pure architecture is a vital factor in recording the precise and perfect idea of architecture as the world of pure blocks. ICHOT is situated opposite the Poznań cathedral in an area where the Polish idea of state was born. In this historically priceless area, the architects built a stark rectangular form which was designed as the background for Ostrów Tumski monuments. The importance and hierarchy of this place are emphasised by a diagonal slot cutting through the concrete set of ICHOT – a glass “split” of the block opens the view from the inside onto the towers of the cathedral. The designers said: “the museum was built from concrete and light” – but also from the ideal geometry of a square. Indeed, the building attracts attention because of its unusual simplicity of space, where the light of concrete architecture creates the shape of a selfless thing – an artefact filled with a pure image of a monolith. ICHOT refers to Claude-Nicholas Boullée’s theory of *beauty as the system of relations*.



Fig. 3. AD ARTIS Studio, *The Gate of Poznań* – the Interactive Centre of the History of Ostrów Tumski, 2014

A mutual arrangement of masses, together with light and shade, will convey the impression connected with the character of the building. In this building without exhibits (there are only multimedia and educational presentations), the interior of the building is as minimalist as its exterior; black dominates in the hall and the corridors. The floors were made from basalt plates. The ticket office and the information point were covered with black plate, some walls are also black. This stark monolithic space should focus the visitors' attention on the exhibition.

The simple and subtle concrete majesty of these solutions might stir emotions. However, the consistent feeling of the geometry of the building is based on the conviction that the idea incorporated in the building can resist the cultural-civilisation changes and that is the essence of searching for contemporary meanings. ICHOT building proves that a simple block might be a striking realisation of an idea through the impression of geometry in concrete and establishing the connections between its physicality, minimal purity and the substance of the programme. Conservatism referring to the timeless qualities of architecture within the material meanings or a mannerist geometrical simplicity of forms might become a way in the search for timelessness.

The building **Infinity Dreams** (designed by Przemko Lukasik and Lukasz Zagala from Medusa Group, 2012; Fig. 4) depicts the rationalisation of form and the unpretentious treatment of concrete. This small office building in Gliwice is a model example depicting the principle of "a mute form" – which refers to the idea of ascetic architecture where architects used purely IT and economic thinking. The austerity of the building and a technical or even industrial character of the interior proves the profound awareness of a building process, the acceptance that the physicality affects the final result of design; the awareness of the material and the technology. A paradigm for this type of architecture is obviously the style of Swiss architects from Eidgenossische Technische Hochschule (ETH) in Zurich. The models seem to be the works of Peter Märkli (*Gantenbein House* in Grabs, 1995), Luigi Snozzi (*Guidotti House* in Monte Carasso, 1984) or Anette Gigon and Mike Guyer (*Substation* in Zurich, 1999). In the 1990s, these works established the foundations of thinking about the relations/connections between an idea and matter in the concrete stylistic of rationalism.

In the Gliwice building, prefabricated elements/units were chosen as the main material – the material that becomes an excuse to search for aesthetics "without qualities", showing a nonchalant detail as the effect of a joint between the austere technology of prefabricated concrete, exposed installations and the smoothness of glazing and floors. *Infinity Dreams* in its programme and "genetic" simplicity and the roughness of detail creates its own code, which creates an endless range of systems in an a priori programmed process of creating architecture. According to the authors – these are not avant-garde or contemporary actions – this is just the idea for contemporary architecture where there is space to reveal the rules of design and also space for the traces left by the used tool which is concrete.

Medusa Group rhetoric of architecture reveals/discovers one more logic of using concrete as the ethical material – revealing its material honesty and technological simplicity. We owe it to Le Corbusier¹⁸ – the first time when it was accepted that an unhidden defectiveness of the material might become the tool of the moral message of architecture. Up to now, the defectiveness of concrete has become an ethical cognitive tool – the function of showing the world as it is, a message hidden in matter that the true beauty is the quality of virtues, not bodies.

Such architecture gives a man the sense of identification, which is his basic psychological need. When we define the qualities of concrete architecture, we must emphasise the superior relations between a structure and its aesthetic meaning – which create a contemporary meaning of the word decorum. It is for decorum that the architects from Medusa Group try different forms in their search for artistic expression in a physical structure.



Fig. 4. Medusa Group, *Infinity Dreams*, Gliwice 2012



Fig. 5. W. Obtulowicz, *Com-Com Zone*, Kraków 2008



The Com – Com Zone building (designed by Wojciech Obtulowicz, 2008; Fig. 5) in Nowa Huta in Kraków follows the same trend. The leisure centre is a clear compositional image. It incorporates elements required by the programme: pitch areas, small architecture, water spaces, footbridges, half-pipes, an amphitheatre. Everything created in concrete – that is why the designed space is perceived as the coherent whole. A 16-metre high viewing tower is a structurally important architectural element.

Both, the exterior and the interior of the object are built from monolith, cast without any special care about the arrangement of the formwork tops and face structures. It gives the object its stark industrial character. Obtulowicz's work does not pretend that masses of reinforced concrete are something more than just a building material. The building lacks any detail work – the walls only reflect a basic technological process. Pitches, a swimming pool, a skate-board square are covered with a homogenous structure of steel skylights resembling factory roofs. To highlight the socio-aesthetic meaning of the object, the architect revealed the interior arrangements of the structure, its passageways, installations and downspouts. This was the architect's way of showing the young people who use the object the anatomy of buildings and their technological solutions. Raw concrete is the outside shell of the hall – it is also the main material used for the interior. The naturalness and authenticity of the building rely on the idea of architecture understood as copying lifestyle – one of the concrete walls was left to be decorated by graffiti artists. Such architecture creates a dynamic picture of a building written in a plan of a city in a language of foreshortening and recapitulation of context, a briefly drawn sign in the space of a city.

Obtulowicz admitted that he had always dreamt about creating such a building “sculpted in concrete”. With that design, he wanted to prove that concrete still works perfectly for architecture and it is unfair to treat it as a plain, coarse material. A decisive character of the object was an architectural counterpoint for dull and expressionless public buildings, which were built during the time of economic transformations in Poland. He once said: “Architecture must be devoid of pathos; it must be simple and functional”.

The question regarding the rules of adequate building has always appeared in the theory of architecture. Mies van der Rohe reminds us that the essence of architecture is understanding *how one stone is laid on the other*. If architecture is an attempt to organise space, therefore a structure is the organisation of matter to stabilise the object. Hence, the importance of the used material and the understanding of the ways of bonding – in order to prolong its life. Owing to that, architecture is not only the art of forms, but it is mainly the art of structural things. As in music, an individual note moved to another staff will cause changes in the melody. In the same way, mortar between stones or formwork may define artistry, precision or their lack in an artist and his work.

The works of Bolesław Stelmach refer to the words of Mies van der Rohe – architecture must have a ritual subtext and logic consisting in the fact that each thing should revive another thing through arrangement, repetition and profound understanding, transformation and purification of structural principles. This situation might be treated as giving the forms their “representative” character and the beginning of transforming technique into architecture. However, it seems that the architect limits the range of the search for perfection: architecture is such a transformation, which moves from the principle of decorating to the search for adequate forms.

In his search for “adequate” forms, Stelmach looks for the qualities of architecture created through subtracting. The architect says that subtracting must be a feature of each moment of a designing and building process. Each stage must find its own quality in the conjunction of reduction – “only then they become as obvious as digging a hole or building a hill”. The search for a reduced structure is the way to the idealised simplicity of geometry, the used materials or their finishing work. A reduction to three or four materials creates opportunities for a stronger reception of individual spaces.

Stelmach proves in all his works that by building out of raw “rational” concrete, one can create a variety of forms, which can trigger/provoke different moods, emotions and impressions. **The Park of Science and Technology in Lublin** (2014; Fig. 6) or *Zana House* (2008) were built from the simplest concrete, which, completed with glass, steel and wood, retained the rigor of thinking about the idea of architecture as something affecting senses. By diversifying the texture of materials, Stelmach created sensual planes, which were far from the traditional interpretation of minimalism. This way of treating material coexists with maximally simplified blocks of buildings. All of it creates the harmonious, serious balanced whole, which corresponds well with the function of the object.

According to this assumption, each building “substance” composes the weight or lightness, smoothness or roughness, peace or anxiety. One may think that a building and a detail should have only as much as it is necessary to create a perfect building – nothing can be subtracted here without losing its quality. A characteristic feature of Stelmach’s architecture is to show the technology used to create a building – each space must reveal the technique of creating a fragment or a detail. Formwork traces, welds of steel elements, visible knots and screw connections of the substructure must speak through their “honesty” of treatment. What is more, they should become information about the structure and the process of building [2, p. 124–128]. Each detail should strengthen the sense of realism in the object and create the essence of this architecture – lasting in time beyond styles and trends.



Fig. 6. B. Stelmach, The Park of Science and Technology, Lublin 2014

References

- [1] Gombrich E.H., *Zmysł porządku. O psychologii sztuki dekoracyjnej*, Kraków 2009.
- [2] Stelmach B., *Poszukiwanie struktur/In Search of Structures*, Vol. 1. *Prace architektoniczne 1997–2011/Architectural Works 1997–2011*, PAN o/Lublin.

Peter Gyori (gyori.peter@phd.uni-szie.hu)

Albert Fekete

Agnes Herczeg

Department of Garden Art, Faculty of Landscape Architecture and Urbanism, Szent Istvan University, Budapest

SIGHT AND INSIGHT

– CREATING SPACE FOR RELIGIOUS PRACTICES

WIDZENIE A POSTRZEGANIE

– TWORZENIE PRZESTRZENI DLA PRAKTYK RELIGIJNYCH

Abstract

The paper reviews some recent attempts that describe the meaning of dry gardens that can be found in Zen Buddhist monasteries in Japan. When researchers try to figure out the meaning of the visual elements, its structure or the placement of the stones, they usually stay on the level of understanding. However, the daily meditational practice among these walls near the dry garden provides a different point of view. The purpose of this study is to show the importance of attention regarding the daily use of dry gardens on the way to enlightenment.

Keywords: dry garden, Buddhism, Zen, practice, attention

Streszczenie

Praca przedstawia bieżące próby przedstawienia znaczenia ogrodów skalnych obecnych w buddyjskich klasztorach zen w Japonii. Podejmując próbę dotarcia do znaczenia elementów wizualnych, struktury ogrodu i ułożenia skał, naukowcy zazwyczaj pozostają na poziomie zrozumienia. Jednak codzienna medytacja w tym otoczeniu pozwala na rozwinięcie innego punktu widzenia. Celem niniejszego badania jest ukazanie, jak ważną rolę pełni uważność w kontekście regularnego korzystania z ogrodów skalnych na drodze do oświecenia.

Słowa kluczowe: ogród skalny, buddyzm, zen, praktykowanie, uważność

1. Introduction

This study discusses some recent attempts that describe the meaning of dry gardens that can be found in Zen Buddhist monasteries in Japan. These gardens are religious sites where monks strive to reach enlightenment by intense meditational practice. When researchers try to figure out the meaning of the visual elements, its structure or the placement of the stones, they usually stay on the level of understanding.

However, the daily meditational practice among these walls near the dry garden provides a different point of view. During a Buddhist meditation, the subject of the beginner's attention is breathing. If thinking or imagination arise besides breathing, then the practitioner realizes it and the attention returns to breathing. As it seems, it is the attention and not its subject that has a significant role from the beginning of the practice.

The purpose of this study is to show the importance of attention regarding the daily use of dry gardens on the way to enlightenment.

2. The emergence of karesansui gardens

In the following section, the emergence of karesansui gardens will be presented through some examples by investigating ancient historical texts from the eighth century, showing the influence of Buddhism regarding the relation to the world, reviewing the philological aspects and explaining the stories and images connected to these gardens.

2.1. Historical texts

A Paekche king sent an image of Buddha to a Japanese emperor along with Buddhist texts written in Chinese characters and perhaps a Buddhist monk by the middle of the sixth century [1, p. 10]. At that time, Japan had no written language, no written history and no written culture. Through the introduction of Buddhism, they received an almost a thousand-year-old written, religious, philosophical system.

The oldest written book about the history of Japan is the *Kojiki*, also known as *Records of Ancient Matters*. A few years later, a much more elaborated and detailed book was written called the *Nihonshoki - Chronicles of Japan*. In these literatures, several uses of stone have been mentioned to demonstrate the relation between the people and the world. The first example from the *Kojiki* shows a religious aspect of this connection from the 2nd century:

“The emperor was playing the cither, and the OPO-OMI TAKESI-UTI-NÖ-SUKUNE abode in the ceremonial place in order to seek the divine will” [2].

The ceremonial place is a garden with sand or grit according to Japanese version of this text. Before the appearance of Buddhism and before the introduction of literature, the Japanese had an oral tradition called Shinto. White sand or gravel was used in Shinto to symbolize purity, and it was used around shrines, temples, and palaces. Shinto had started building shrines near or even on sites that had been worshipped for centuries before [3, p. 20]. These

sites are called iwakura, a formation of rocks to which a kami is invited to descend for worship, which are considered to be holy ground [4].

The second example from the *Nihonshoki* demonstrates a specific use of stone to create a scenery of a landscape at the beginning of the seventh century: “Moreover, I have a small talent. I can make the figures of hills and mountains. If you kept me and made use of me, it would be to the advantage of the country” [5].

According to the text, Suiko empress had him build the Mount Sumeru and a Wu-bridge at the southern courtyard. The stones started to symbolize the central Buddhist image of Mount Sumeru, known as Shumisen in Japanese. Shumisen is the legendary central mountain in Buddhist cosmology; eight lower mountains and an equal number of seas encircle it. This idea was easily adopted, because it was familiar to the previously used sacred area called iwakura [6, p. 17].

2.2. Influence of Buddhism

Buddhism began to spread throughout Japan during the Heian period (794-1185). In these times, two types of gardens were built, the residences of aristocrats and the temples of Buddhist sects [7, p. 20]. The designers of lay gardens were mainly aristocrats, who conduct the building of their own garden and gave advices to others. They were garden masters of their age, described in *Sakuteiki*¹ as the “skilled ones of old”. Later, there were Buddhist priests who participated in garden building, known as *ishitatesō*, literally stone-setting priests [8]. The stones became symbols of Buddhism and tools for the scenic arrangement of the nature.

At that time, Buddhist monks visited China to seek greater truth, to learn from highly trained Chinese masters. Myōan Eisai was the first Japanese, who not only practiced in Chan² Buddhist monasteries, but became the master of the so-called Linji-school. Later, he introduced Chan Buddhism to Japan and established several monasteries. With the arrival of Zen Buddhism in the Kamakura period (1185–1333), the focus changed to the inner workings of the mind. The quest was to penetrate to the truth hidden beneath the surface reality of life and nature. This drive toward inner truth led to gardens replicate the inner essence of nature rather than its outer forms [3, pp. 24–26].

According to a historical text from the fourteenth century, the three main purposes of dry gardens were to provide the places for *zazen*³, poem writing, and enjoying the landscapes of seasons [9].

¹ *Sakuteiki*: a gardening manual from the mid-Heian period, describes in detail the technique and theory of garden design.

² Chan in China, Zen in Japan, Son in Korean, and Thien in Vietnam. Those names correspond to the pronunciation of the Sanskrit word *dhyana* (“meditation”).

³ *Zazen* is a meditative discipline that is typically the primary practice of Zen Buddhism. It can be regarded as a means of insight into the nature of existence.

2.3. Concepts behind karesansui

From the middle of the Heian period, a new garden style was introduced called karesansui gardens. The Sakuteiki describes it as a garden without ponds and streams [8]. It literally means “dry mountain water”.

According to Sakuteiki, the word used for nature is shōtoku no senzui, which means “innate disposition of mountain-water”. The senzui not only refers to mountain and waters, but it can also imply a landscape appearing not in the shinden-style garden of aristocrats, but in Buddhist temples as well. It also means “nature” [10, p. 17].

There is another word karagu, from which the term karesansui can be originated. Since the kara was written using several variants of characters, it can be assumed that the original meaning was not „dry”, as we think today, but „to reveal”. The placement of the stones without any watercourse, so that the bottom part of the river would be hidden by water, was visible [11, p. 119].

2.4. Stories and images

a) Dragon’s gate waterfall

The Sōgenchi Garden, located behind Tenryū-ji, is one of the oldest landscape gardens in Japan, retaining the same form as when it was designed in the fourteenth century by Musō Soseki. In the back of the garden, dynamic arrangements of large stones against the hillside are representing the scenery of a mountain ravine. The central feature is the Ryūmon-no-taki, a composition of standing boulders representing a waterfall [12]. In China, there was a legendary river with a powerful three-tiered waterfall. If a fish proved strong and determined enough to swim to the top, the fish would be transformed into a dragon. Historically, the dragon was the symbol of the emperor of China, and the dragon gate was a metaphor for passing the very hard examinations required for imperial administrators [13, p. 59]. In Japan, it is allegorical to Zen study and enlightenment through intensive self-training and meditation [6, p. 63].

b) Tigress crossing the river with her cubs

The dry garden at Ryōan-ji was called the garden of the Tiger Cubs Crossing the River in the late eighteenth century. This was a very conventional way of describing gardens at the end of the Edo period. A tigress gave birth to three cubs, but one was a panther. If the mother tiger was not constantly on guard, the panther cub would eat the other cubs. The tigress and cubs had to cross a river, but the mother tiger could only carry one cub at time. How was the mother tiger going to carry the three cubs across the river so that the panther cub would not eat the two tiger cubs? It has another meaning, in which a Chinese governor was assigned to an area to solve a situation caused by a rampaging tiger [14, pp. 107–108]. Both stories use an attitude, which easily can be connected to Buddhist practice: be on guard, to be very attentive.

c) Strokes of the Japanese character for the heart or the mind

At the end of fourteenth century, a pond style called Shinji-chi appeared at Kitatoji-ji temple, which was the family temple of Ashikaga shoguns. The shape of the pond was a cursive

rendering of a kanji character for heart (or mind) [15, p. 467]. Besides the relation of the heart to the Zen Buddhist teachings, ponds often were shaped to the form written characters for esoteric reasons [16, pp. 136–138]. In this case, the pattern of the stones draws the character of the heart.

d) Waves of the ocean and sacred mountains

The raked sand or gravel recalling waves or the rippling ocean. The symbolism came from Shinto, where a white sand area symbolized a sacred ground where a kami can appear. Regarding its maintenance, it has a practical function because a dry garden requires intensive daily care [13, pp. 82–87], which is also a meditational practice.

The image of a sacred mountains refers to Mount Sumeru of Buddhist cosmology, a Taoist mountain with eternal life called Hōrai or a holy place such as Mount Fuji, where gods reside [13, pp. 54–58].

3. Approaches on the level of understanding

The following studies use scientific methods of anthropology, psychology, psychotherapy, and philosophy to find answers in relation to the creation and use of dry gardens in order to understand their structures, or their meaningful appearance. The common concept of these studies is a hidden feature, a tool for a better understanding of our place in the garden that must be revealed.

a) Unconscious perception of unexpected structural features

The researchers used medial-axis transformation on the layout of the dry garden of the Ryōan-ji temple in Kyoto. It is a shape representation scheme that is applied widely in image processing and in studies of biological vision. The purpose of this study is to draw attention to the unconscious visual sensitivity to axial-symmetry skeletons of stimulus shapes. The resulting image is a simple, dichotomously branched tree that converges on the primary garden-viewing area - the balcony. The pattern of this image is a self-similar tree, with the mean branch length decreasing monotonically from the trunk to the tertiary level [17].

b) Scene Perception and Visual Segmentation

The four major aesthetic ideals displayed by dry gardens are asymmetry, tranquility, simplicity and naturalness. In this work, the researchers applied Gestalt⁴ principles of visual grouping to understand and reconstruct the karesansui design structure in order to achieve these aesthetic qualities. The process of visual segmentation into figure and ground may lead to naturalness and avoid excessive local “pop-out” by careful choice and controlled use of various design elements [18].

⁴ Gestalt psychology is a philosophy of mind of the Berlin School of experimental psychology. It is an attempt to understand the laws behind the ability to acquire and maintain meaningful perceptions in an apparently chaotic world.

c) A Phenomenological-Anthropological Approach

When paying attention to the details of the garden, instead of merely reducing them to ideas to be extracted, it becomes apparent that seeing is not necessarily authoritative in the perceptual order. Audition and tactileness are as relevant as vision. The actuality of the garden is felt and sensed as much as it is there to be read as a text with the eyes. Openness to sensory engagement and the felt actuality reveals the ways in which a meaning is given, communicated to, and becomes part of the visitors' experience. Exploring the visitors' sensory perceptions also raises the complex question of how humans form and constitute their reality [19].

d) The Garden as a kōan⁵ of Perception

This approach demonstrates a firsthand experience to find out a working method to see and understand the hidden, invisible feature of the garden. The conceptual problem that was found during the course of the research was related to the act of taking the mountain that is physically outside and bringing it into the garden and to its viewers, and how to bring the viewers to the mountain and the nature that exists beyond the garden wall. This problem has a practical aspect - how can a designer present the mountain in a manner which will provide it with a frame and thus excise it from its everyday context; on the other hand, how can he present the mountain "as it is", simply as a mountain [20].

4. Attitudes toward enlightenment

A practical method will be presented using the core teachings of Zen Buddhism. It will be emphasized that religious approach through formal, daily practice could change not just the attitudes, but the perception as well.

It should be noticed that the majority of English books on Buddhism use the term "enlightenment" to translate the term bodhi, while the original meaning is much more expressive: the root budh, from which both bodhi (awakening) and Buddha (awakened) are derived, means "to wake up" or "to recover consciousness" [21, p. 1].

4.1. The quintessence of Zen

Bodhidharma was a Buddhist monk who lived during the fifth or sixth century. He is traditionally credited as the transmitter of Chan Buddhism to China and regarded as its first Chinese patriarch. According to Chinese legend, he also began the physical training of the monks of Shaolin Monastery, which led to the creation of Shaolin kungfu. In Japan, he is known as Daruma [22].

⁵ A kōan is a story, dialogue, question, or statement, which is used in Zen-practice to provoke the „great doubt“, and test a student's progress in Zen practice.

Bodhidharma is traditionally seen as introducing dhyāna-practice (meditation) in China. According to the tradition, one of the fundamental Chan texts attributed to Bodhidharma is a four-line stanza whose first two verses echo the Lankāvatāra Sūtra's disdain for words and whose second two verses stress the importance of the insight into reality achieved through "self-realization" [23, p. 85].

*A special transmission outside the scriptures;
Not dependent on language and texts;
Pointing directly to Mind;
See your true nature and become Buddha.*

Finding one's own true nature is not dependent on explanation, Sutras, or academic knowledge. No concept can ever express it. Zen teaching points directly to one's own mind. If someone wants to become Buddha, even understanding the Buddha's own speech cannot help to achieve it. Using intellectual understanding to find one's own true nature is like expecting a hungry man to satisfy his agonizing hunger with a picture of a banana. Zen teaching says, "Open your mouth. Here is a banana. Now eat!" [24, p. 210].

The other important term from the last line goes back to the method of awakening. The time-honored Chan/Zen expression for enlightenment is "seeing the nature". To "see" one's own original, true nature is to discover and experience the universal Buddha-nature, which is inherent in all beings whether they are enlightened or not [25, pp. 88–89].

4.2. Living by vow

Many Buddhists are familiar with the Four Great Bodhisattva Vows. Some people seem to have the impression that this is an almost exclusively Zen thing, but most of the Japanese traditions recite the Vows, along with Korean and Chinese schools. The Bodhisattva vow is taken by Mahayana Buddhists to liberate all sentient beings.

*Sentient beings are numberless; I vow to save them.
Desires are inexhaustible; I vow to put an end to them.
The dharmas are boundless; I vow to master them.
The Buddha's Way is unsurpassable; I vow to attain it.*

Each of these vows is a wonderfully large and impossible proposition when set against our limited human means [26, pp. 30–32]. This means that the practice is endless and that one cannot completely fulfill the four vows.

However, "vow" is not a suitable term to express the meaning of the Sanskrit pranidhāna. Pranidhāna, which is a strong wish, aspiration, prayer, or an inflexible determination to carry out one's will even through an infinite series of rebirths" [27, p. 307].



In daily life, the mind is running uncontrolled; the attention is jumping from one idea to another, without an ability to exert any control over it. Without taking any clear decision to prevent some things and foster some other things, it is rather difficult to keep in mind these vows in different situations during daily life, and secondly, it is difficult to apply them. But if the practitioners formalize their decision by making a vow every day after meditation, during practice or ceremonies, then it will surely leave a strong imprint on themselves. It will be a constant attitude changer, a long-term determination on the path of compassion and wisdom. For this reason, a bodhisattva is a person who lives by vow instead of by karma. Karma means habit, preferences, or a ready-made system of values. As we grow up, we learn a system of values from the culture around us, which we use to evaluate the world and choose actions. This is karma, and living by karma. In contrast, a bodhisattva lives by vow. Vow is like a compass that shows the direction toward the Buddha [28, p. 15].

4.3. The surrounding space

The monk Myōan Eisai (1141–1215) is regarded as the first to establish a branch of the Linji Chan (Rinzai Zen) lineage in his native Japan. Eisai visited a number of the leading monasteries in Zhejiang on two separate trips to China in the twentieth century. He trained under Chan master who was abbot at the Wannian Monastery on Tiantai Mountain in Taizhou, and then abbot at the Jingde Chan Monastery on Tiantong Mountain in Mingzhou. In the decade following his return to Japan in 1191, Eisai founded Song-style monasteries in Kyūshū (Shōfuku-ji), Kamakura (Jūfuku-ji), and Kyoto (Kennin-ji). The Kennin-ji was an excellent replica of the public monasteries in Zhejiang in the thirteenth century [29, p. 139–142]. At the beginning, the garden of Zen temples looked like Chinese gardens of that time [30, p. 472]. It was not unusual during the importation of Chinese culture to replicate spaces and materials in Japan; however, making an exact copy of the surrounding space in this case could be connected to previous spiritual experience in Song-style monasteries in China. So, for Eisai, the experience might have been related to space and space might have been linked to experience as an inspirational way.

Following the footsteps of Eisai, Dōgen, who went to study at Kennin-ji temple, also visited and trained at major Chan monasteries in China. After he came back to Japan, he devoted his life to replicate and maintain the Song-style monastic training system. He emphasized independence by ascetic meditation in the mountains away from the capitals, bodhisattva-precepts ordinations apart from the Tendai monopoly, and thorough Chan monastic routines. His attitude towards the monastic space shows a direct approach of Zen practice:

“When we make a vow to fund a temple (a sangha or a monastery), we should not be motivated by human sentiment, but we should strengthen our aspiration for the continuous practice of Buddha Dharma.” [28, pp. 43–44].

The previously mentioned dragon gate waterfall at Tenryū-ji temple could be another example for inspiration based on practice. The monks strive with a seemingly impossible task to achieve the top of the waterfall just like fish. The tiger cubs’ image of the stones also reflects the effort to be constantly on guard during the practice.

5. Conclusion

It has been demonstrated that the religious aspect has a significant influence on the outcome of researches on monastic gardens. The interpretations have direction regarding the attention of the researcher, which affects the way of one's relation to the gardens. Scientific methods generate questions like:

- ▶ How was the garden created?
- ▶ What is hidden in its structure?
- ▶ How does it influence our experience?
- ▶ How does it work?

In these cases, the subject of attention is the garden itself, or its influence on the observer. Therefore, the direction of attention is directed from the observer to the subject in order to understand something about it.

On the other hand, the Zen Buddhist perspective clearly states that the direction must be inverse. It shows that the purpose of the structure of the monastic environment has a very distinct role in the life of monks. For this reason, the oral or written historical interpretations of a monastic garden must be seen through a practical eye. As it seems also in the case of vows and commitment, they enforce the Buddhist practice and develop some specific characteristics of our mind. By formalizing the decision and by making a vow every day during the practice, it will surely leave a strong imprint on oneself. By formalizing the space as a vow, seeing the space as a vow is a skillful means of strengthening one's aspiration "to reveal" and see one's true nature. Dōgen demonstrated the way of this practice by the example of establishing a monastery:

"Listen to the sound of raindrops at midnight. The raindrops have the power to pierce not only moss, but also rock."

So, the sitting produces the power to erode a rock as we sit moment by moment, day after day, year after year. When we think of establishing a monastery, it is the same. Our effort is like raindrops; it does not create change in one day, or a few days, or a few years. But if we just keep doing it, when conditions are ripe, it happens [28, pp. 48–49].

References

- [1] Craig A. M., *The heritage of Japanese civilization*, Prentice Hall, Boston 2010.
- [2] Japanese Historical Text Initiative, *Kojiki*, Book 2, Page 60, Para 6, <https://jhti.berkeley.edu/cgi-bin/jhti/select.cgi?honname=2> (access: 01.10.2017).
- [3] Mansfield S., Richie D., *Japanese stone gardens: origins, meaning, form*, Tuttle Publishing, North Clarendon 2009.
- [4] Encyclopedia of Shinto, *Iwakura*, <http://eos.kokugakuin.ac.jp/modules/xwords/entry.php?entryID=251> (access: 01.10.2017).
- [5] Japanese Historical Text Initiative, *Nihonshoki*, Chapter 22, Page 1307, Para 2, <https://jhti.berkeley.edu/cgi-bin/jhti/select.cgi?honname=1> (access: 01.10.2017).
- [6] Keane M.P., Ohashi H., *Japanese Garden Design*, Tuttle Publishing, New York 2012
- [7] Keane M.P., *The Japanese tea garden*, Stone Bridge Press, Berkeley 2009.



- [8] Takei J., Keane M. P., *Sakuteiki. Visions of the Japanese Garden*, Tuttle Publishing, North Clarendon, 2008, Para 123 (epub).
- [9] Sekinishi T., *Study on the Zen garden view in the late 14th century with reference to „Kuuge-Nichiyou-Kufuu-Ryakushu”*, Journal of The Japanese Institute of Landscape Architecture, 75-5 / 2012, 367–372.
- [10] King J., *Beyond the great wave: the Japanese landscape print, 1727–1960*, Peter Lang, New York 2010.
- [11] Mizuno K., Ono M., *The hidden gardens of Kyoto*, Kodansha, Tokyo 2004.
- [12] Rinzaï-Obaku Zen, *Tenryū-ji, a U.N. World Heritage Site*, http://zen.rinnou.net/exhibition/ex_01.html (access: 01.10.2017).
- [13] Goto S., Naka T., *Japanese gardens: symbolism and design*, Routledge, New York 2016.
- [14] Yamada S., *Shots in the dark*, University of Chicago Press, Chicago 2011.
- [15] Daniell T., Seki A., *Houses and gardens of Kyoto*, Tuttle Publishing, North Clarendon 2010.
- [16] Johnson N. B., *Tenryū-ji: life and spirit of a Kyōto garden*, Stone Bridge, Berkeley 2012.
- [17] Van Tonder G. J., Lyons M. J., Ejima Y., *Perception psychology: Visual structure of a Japanese Zen garden*, *Nature*, 419-6905/2002, 359–360.
- [18] Van Tonder G. J., Lyons M. J., *Visual Perception in Japanese Rock Garden Design*, *Axiomathes*, 15-3 / 2005, 353–371.
- [19] Katahira M., *Approaching Zen Gardens: A Phenomenological-Anthropological Approach*, [in:] *Gardens and the Passion for the Infinite*, eds. A.-T. Tymieniecka, Springer, Dordrecht, 2003, 69–84.
- [20] Ronnen G., *The zen garden of Shōden-ji as a Kōan of perception*, [in:] *From the things themselves: architecture and phenomenology*, eds. B. Jacquet, V. Giraud, Kyoto University Press, Kyoto, 2013, 61–106.
- [21] Cohen R. S., *Beyond enlightenment: Buddhism, religion, modernity*, Routledge, London 2006.
- [22] Encyclopædia Britannica, *Bodhidharma*, <https://www.britannica.com/biography/Bodhidharma> (access: 01.10.2017).
- [23] Dumoulin H., Heisig J. W., Knitter P. F., *Zen Buddhism: A history, India and China*, World Wisdom, Bloomington 2005.
- [24] Seung S., *The compass of Zen*, Shambhala, Boston 1997.
- [25] Kraft K., *Eloquent Zen: Daitō and early Japanese Zen*, University of Hawaii Press, Honolulu 1992.
- [26] Murphy S., Tarrant J., *Upside-down Zen: finding the marvelous in the ordinary*, Wisdom Publications, Boston 2006.
- [27] Suzuki D.T., *Outline of Mahayana Buddhism*, Lusac and Company, London 1907.
- [28] Okumura S., *Living by vow: a practical introduction to eight essential zen chants and texts*, Wisdom Publications, Boston 2012.
- [29] *Zen classics: formative texts in the history of Zen Buddhism*, eds. S. Heine, D.S Wright, Oxford University Press, New York 2006.
- [30] Baridon M., *Les jardins: paysagistes, jardiniers, poètes. Bouquins*, R. Laffont, Paris 1998.

Magdalena Rzeszotarska-Palka (mrzeszotarskapalka@zut.edu.pl)

Department of Landscape Design, Faculty of Environmental Management and Agriculture,
West Pomeranian University of Technology in Szczecin

HEAVENS ABOVE – A STATUE OF CHRIST IN THE LANDSCAPE

PONAD NIEBIOŚA – POMNIK CHRYSZTUSA W KRAJOBRAZIE

Abstract

The monuments of Christ erected from 1920s onwards in many places throughout the world are a specific group of dominants associated with sacrum. Their effect on the perception of the landscape is very strong because of the artistic form and, above all, the symbolic dimension they have. The aim of the work is to demonstrate that land development projects around sacred landscape dominants in the form of statues of Christ should be subject to careful consideration, both in terms of functionality and composition. The adjustment of the environment to the scale and rank of the object - so as to emphasise its special role in the landscape, but also the symbolism associated with the sphere of sacrum - plays a crucial role in this case. Comparative analyses were made for ten highest statues of Christ in the world. The research was also supplemented with a presentation of the concept of land development around the statue of Christ in Świebodzin.

Keywords: landscape dominants, sacrum in the landscape, statue of Christ

Streszczenie

Pomniki Chrystusa wznoszone od lat 20. XX wieku w wielu miejscach na świecie stanowią specyficzną grupę dominant związanych ze sferą sacrum. Ich oddziaływanie na percepcję krajobrazu jest szczególnie silne ze względu na formę artystyczną, a przede wszystkim symboliczny wymiar. Celem pracy jest wykazanie, że projekty zagospodarowania terenu wokół sakralnej dominandy krajobrazowej, którą stanowią pomniki Chrystusa powinny być starannie przemyślane pod względem funkcjonalnym i kompozycyjnym. Kluczową rolę odgrywa w tym przypadku dostosowanie otoczenia do skali i rangi obiektu – tak aby podkreślić jego szczególną rolę w krajobrazie, ale również symbolikę związaną ze sferą sacrum. Analizie porównawczej poddano dziesięć najwyższych na świecie pomników Chrystusa. Badania porównawcze zostały również uzupełnione o prezentację koncepcji zagospodarowania terenu wokół pomnika Chrystusa Króla w Świebodzinie.

Słowa kluczowe: dominanty krajobrazowe, sacrum w krajobrazie, pomnik Chrystusa

1. Introduction

Spatial dominants in the urban landscape are primarily skyscrapers and engineering structures, but also castle towers, town halls and church towers. The specific group of dominants associated with the sacred are the monuments of Christ erected from 1920s onwards in many places throughout the world - on the outskirts of cities and in the open landscape. Like all high objects, they change the key elements of the landscape's scenic structure, such as: distant viewpoints, high-rise landmarks, or the silhouette of city panoramas [2, 3, 10, 14]. The impact of scaled high objects on the landscape is difficult to define and shape; still, such objects occurring in groups in urbanised space can create seemingly neutral vista backgrounds for other elements of the city landscape [17]. At the same time, according to Oleński: "one high-rise tower can be more visible in the city skyline than a cluster of high-rise buildings" [14]. Monumental statues of Christ have a similar effect on the perception of the landscape, with their impact being even stronger because of the artistic form and, above all, the symbolic dimension they have [11]. "Thanks to symbolism, architecture can form means of communication through the intentional, and independent from aesthetic and practical reasons, introduction of content elements – signs that evoke emotional reactions. The symbolism of the landscape can be demonstrated in the presence of symbolic objects, in the relations of the building to the surrounding space, in the symbolic shapes of the design and in the features of form, in the presence of archetypes, allegories and metaphors" [7]. The way of managing its immediate environment and location in the landscape is no less important than the very artistic form of the statue of Christ.

2. Aim and methods

The subject of the research is the specific landscape dominant associated with religious worship, in the form of statues of Christ located in many places around the world. The basic criterion for the selection of objects for analysis was the height of the monument, without taking the height of its base into account. The highest Christ statues, which are 20 to 33 meters high, were then ordered from the highest to the lowest. The analysis covered the location of the object in the landscape, the way of managing the nearest surroundings of the object, active and passive exposure, landscape dominants, with particular emphasis on the possible perception of the monument from the nearest town. The analyses were conducted on the basis of topographic maps of the areas, the available photographic documentation, descriptions and site inspections conducted in Świebodzin and Lisbon. The test results are summarised in a collective table.

The comparative research was also supplemented with a presentation of the concept of land development around the statue of Christ in Świebodzin executed under the supervision of the author of the present article in 2007.

The aim of the work is to demonstrate that land development projects around the sacred landscape dominants in the form of statues of Christ should be subject to careful consideration,

both in terms of functionality and composition. The adjustment of the environment to the scale and the rank of the object – so as to emphasise its special role in the landscape, but also the symbolism associated with the sphere of *sacrum* – plays a crucial role in this case.

3. Statues of Christ in the landscape

At the beginning of the 1920s, colossal statues of Christ began to appear in the landscape, most of them in Latin America. Currently, there are 27 such monuments around the world, which are over 20 m high. None of them are as tall as the Buddha statue in Asia (Spring Temple Buddha), which is 128 meters high. The first object of this type was Cristo Redentor built in Rio de Janeiro – “It’s a religious symbol, a cultural symbol and a symbol of Brazil” – quoting Father Omar, rector of the chapel located at the base of the statue: “Christ the Redeemer brings a marvellous vista of welcoming arms to all those who pass through the city of Rio de Janeiro” [4]. Listed below are the ten highest statues of Christ in the world, ranked from the highest to the lowest (as of December 31, 2017). The test results are summarised in a collective table (Tab. 1.)

3.1. Christ the King Statue (Christ the King), Świebodzin, Poland

Świebodzin is home to the world’s tallest monument of Christ the King, which is 36 meters high and is set on a 16-meter high base facing the town. Its author is Mirosław Patecki from Przyborów near Sława Śląska [19]. The statue was erected on an artificial mound covered with stone boulders (Fig. 1, 2, 3).



Fig. 1. Christ the King Statue – view from the road DK3, Świebodzin, July 2017
(photo by M. Rzeszotarska-Pałka)



Fig. 2. Christ the King Statue – view from the mound, Świebodzin, July 2017
(photo by M. Rzeszotarska-Palka)



Fig. 3. Christ the King Statue, Świebodzin
– view from the parking lot, July 2017
(photo by M. Rzeszotarska-Palka)

3.2. Christ of Peace Statue (Cristo de la Concordia), Cochabamba, Bolivia

The Bolivian statue of Christ was built in 1994 on the San Pedro Hill in the city of Cochabamba. The statue is 34 meters high and stands on a base that is 6.24 meters tall. You can get to it by cable car or by climbing 2000 steps.

3.3. Christ the King Statue (Cristo Redentor), Rio de Janeiro, Brazil

The statue of Christ the Redeemer was erected on the top of the 710-meter-high granite Corcovado Hill. In 1921, the collection of money for the construction of the monument of Christ, which was to commemorate the hundredth anniversary of the independence of the state, began in Brazil. Hector da Silva's project was selected for construction - the statue of Christ with open arms. The head and arms of Christ were designed by the French sculptor of Polish origin, Paul Landowski. The statue measures 30 meters in height and is set on a base that is 7 meters high. The sculpture was made in France and then transported to Brazil. The unveiling of the monument of Christ the Saviour took place in 1931 and was conducted by the lighting designer Guglielmo Marconi, who switched the illumination of the statue on from a yacht moored in the port of Italian Genoa. You can reach the monument by road or cable car, and then climb to the observation deck at the base with 222 steps, or take the lift or escalator instead. Nora Heimann, dean of the Department of Art at the Catholic University of Rio, says that Cristo Redentor stands out because it is a bridge between the classic European images of Christ on the cross and the more modern, less formal styles. According to Encyclopedia Britannica, Cristo is also the world's largest Art Deco sculpture.

3.4. Christ of the Knoll (Cristo del Otero), Palencia, Spain

Cristo del Otero monument was erected in 1931 according to the design of the sculptor Vitorio Macho in the style that combined Art Deco with elements of cubism. The height of the monument is 21 meters. It is located on a stone hill in near the city of Palencia and faces it.

3.5. Christ the King (Christo Rei), Lisbon, Portugal

The monument represents Christ the King with open arms and is a smaller scale copy of Christ from Rio de Janeiro. The 1959 structure measures some 100 meters, but the figure of Christ itself is 28 meters high. The monument is located on the southern bank of the Tagus, some 10 km from the centre of Lisbon (Fig. 4).



Fig. 4. Christ the King, Lisbon. View towards the city, May 2017
(photo by M. Rzeszotarska-Palka)

3.6. Christ of Vũng Tàu, Vietnam

The Vietnamese started the construction of the monument of Christ in 1974 and completed it 20 years later. The monument is 32 meters high, there are stairs inside the statue that lead to the viewing platform.

3.7. Christ the King Statue (Sanctuaire du Christ-Roi), Cerro del Cubilete, Mexico

This statue of Christ is one of the largest monuments of Christ made entirely of bronze and is located on the top of the Cerro del Cubilete mountain in the state of Guanajuato in Mexico. Built in 1940, it is 20 meters tall. At its foot is a sanctuary building with facilities.

3.8. Christ of the Pacific Statue (Cristo del Pacífico), Lima, Peru

The youngest giant statue of Christ, was built in 2011 in the capital of Peru - Lima. The monument is 37 meters high (22 meters tall statue of Christ with crossed arms, standing on a 15-meter pedestal). The construction was ordered by the former president of Peru, Alan García Pérez.

3.9. Christ of the Ozarks, Arkansas, USA

The Americans built their highest Christ statue in 1966 in Arkansas. It measures 20 meters. It is located among wooded hills away from the city. Stephen Colbert, a popular satirist in the USA, mocked the construction of the monument in Świebodzin saying that “the Book of the Apocalypse says that when the judgment day comes, a battle will take place between the greatest monuments of Jesus, and the true Christ will come to a country that will win the fight” [5].

3.10. Christ the Redeemer (Cristo Redentore), Monte San Biagio, Maratea, Italy

The statue of Christ the Redeemer is a tall marble statue, more than 20 meters high, built in 1965 at the top of the Italian Monte San Biagio. The author of the project is the Florentine sculptor Bruno Innocenti. A captivating statue resembling a white angel with outstretched wings was situated on the top of the hill, facing the town and the Tyrrhenian Sea.

Table 1. Comparative analysis of the location of the highest monuments of Christ in the landscape (own study)

| Statue of Christ | Location of the object in the landscape | Development of the nearest surroundings of the building | Active exposure of dominants in the landscape | Passive exposure of dominants in the landscape |
|---|---|--|--|--|
| Christ the King Statue, Świebodzin, Poland | An open area surrounded by cultivated fields, housing development and a shopping centre located some 400m away. | Stations of the cross around the base of the earth mound, unpaved parking lot, catering facilities, sanitary protection zone | Visible from a distance of several kilometres, including a national road, it dominates in the open, flat terrain | Lookout on the mound at the base of the monument – in the foreground, we see the shopping centre, further back, the town |
| Cristo de la Concordia, Cochabamba, Bolivia | On a hill dominating the city, away from buildings (1–3 km) | Hardened square and road leading to the hill with a careful composition of greenery | Visible from a distance of several to several dozen kilometres, it dominates the hill | View of the city in the distance, immediate neighbourhood – composed greenery and hill slope |
| Cristo Redentor, Rio de Janeiro, Brasil | On the steep stone hill of Corcovado, a few kilometres away from the city | A small paved square at the top of the hill, access by steep stairs and a cable car | Visible from the city and the Guanabara Bay from several dozen kilometres, exposed on a steep cliff | Vista point at the base of the monument on the surrounding wooded hills, the waters of the bay, and the city in the distance |

| Statute of Christ | Location of the object in the landscape | Development of the nearest surroundings of the building | Active exposure of dominants in the landscape | Passive exposure of dominants in the landscape |
|--|--|---|---|--|
| Cristo del Otero, Palencia, Spain | On a low hill, on the outskirts of the city, a flat open area | A small chapel and museum in the building at the foot of the monument, a small observation deck, no cultivated greenery | Visible from a few kilometres on a flat landscape | View of the city and farmlands from the buildings at the base of the monument |
| Christo Rei, Lisbon, Portugal | On a hill on the banks of the Tagus River, the city centre is situated on the opposite bank of the river | Extensive area at the foot of the monument's foundation, developed with a careful composition of greenery, vista point on the city and the river, parking, catering outlets | Visible from a distance of several to several dozen kilometres from the city and the Tagus River, it does not dominate the city | View of the city, the river, Vasco da Gamma bridge in the foreground, rhythmic planting of olive trees |
| Christ of Vŭng Tâu, Vietnam | On a wooded hill a few kilometres from the city | A small viewing terrace, wide stairs leading to the foot of the monument, surrounded by natural greenery | Visible on a gentle hill from a distance of several kilometres from the city and the waters of the South China Sea | View of the city and sea waters, panoramic views from the stairs leading to the top |
| Sanctuaire du Christ-Roi, Cerro del Cubilete, Mexico | On one of the hills surrounding the city, a few kilometres from the city, in a hilly area | A large paved square surrounded by a circular building of a sanctuary, a wide access road surrounding the hill | Visible from a distance of several kilometres from the city and access roads, it is a small object in the landscape | A view of the city, surrounding hills, a circular stone square surrounded by a colonnade of a sanctuary building visible in the foreground |
| Cristo del Pacifico, Lima, Peru | On a range of hills located at the Pacific Lima Bay, a few kilometres from the city | Lack of land development, on a sandy elongated hill where degraded buildings are located | Visible from several kilometres from the city and the waters of the Lima Bay, it does not dominate the city | A view of the city and the Pacific, degraded buildings of „favela” visible at the base of the hill |
| Christ of the Ozarks, Arkansas, USA | On one of the many forested hills, a few kilometres from the town of Eureka Springs | A vast grassy glade with an amphitheatre at one end, surrounded by a thick forest | Visible from several kilometres, partially obscured by lush vegetation, it does not dominate its surroundings | View of the glade and open-air amphitheatre, distant views obscured by trees |

| Statue of Christ | Location of the object in the landscape | Development of the nearest surroundings of the building | Active exposure of dominants in the landscape | Passive exposure of dominants in the landscape |
|--|--|--|---|---|
| Cristo Redentore, Monte San Biagio, Maratea, Italy | At the top of Monte San Biagio hill on the Tyrrhenian Sea, a few kilometres from the town of Maratea | A picturesque road supported by arcades carved into the rock that winds up to the top among the ruins of the ancient town of Maratea | Visible from several kilometres from the Tyrrhenian Sea and surrounding towns, it forms the culmination of the highest hill in the area | Vista point at the foot of the monument with an extensive view of the Maratea coast |

4. Results of the analyses

The comparative analysis (Tab. 1.) demonstrated that Christ's statues are usually located a few kilometres from the city or its centre (Lisbon). The only objects located in the immediate vicinity of the building are the statues in Świebodzin – approx. 400 m from a shopping centre and detached housing and in Lima - there are degraded buildings, the so-called "Favelas" at the foot of the hill there. In Lisbon and Palencia, urban development is located a few hundred meters away from the developed area around the monuments. All objects analysed, apart from the Świebodzin Christ, were situated at natural heights that dominate the surrounding landscape.

The way of managing the nearest surroundings of monuments is conditioned by the location – objects erected at the top of steep rocky hills are usually surrounded by a small hardened observation deck. Only the monuments in Lisbon and Arkansas are surrounded by a vast, composed space, constituting the perfect foreground for the exhibition of the dominant. The Christ in Mexico was erected directly on top of the circular sanctuary building that surrounds the stone square. When we compare the land development mode, the worst performers are found in Świebodzin and Lima. In Peru, the area remains undeveloped. In Poland, on the other hand, the Stations of the Cross were placed around the base of the artificial mound covered with boulders and a decorative gate leading from the parking lot. Low quality catering facilities, the unpaved parking lot, as well as a fenced sanitary protection zone located 50 m away, are located nearby.

The best exposed in the landscape are objects located on high hills: statues in Rio de Janeiro, Bolivia, Lisbon, Vietnam and Italy. At the same time, these places also offer beautiful vistas of the neighbouring cities and the diversified surrounding landscape (including rivers, bays, sea waters). The monument of Christ the King in Świebodzin, despite being located on a small hill, dominates the town, and the open flat landscape of cultivated fields surrounding it from the south and the east.

5. Land development plan at the monument of Christ the King in Świebodzin

The proposed land development project around the monument of Christ in Świebodzin was designed in 2007 simultaneously with the construction of the monument itself, as a result of consultations with rev. S. Zawadzki [18]. It uses both compositional elements and vegetation with a symbolic dimension.

Świebodzin is a town with over 20,000 inhabitants in the Lubuskie Lake District, some 80 km from the Polish-German border. The town is an important transport hub through which the following national roads run: the DK2 Berlin–Warsaw–Terespol and the DK3 Świnoujście–Świebodzin–Jakuszyce (Fig. 1). The area where the Christ the King monument was located covers an area of approx. 10 ha located on the outskirts of the town and in the immediate vicinity of cultivated fields. From the north, at a distance of about 500 m, we can find detached housing (Fig. 2), and from the west, the town swimming pool and service areas are located at a similar distance: a large shopping centre with a car park. The dynamically shaped area rises naturally to a height of 12 m in the south-easterly direction, which is why the mound extends a panorama of the town, surrounding farmland and the nearby expressway linking the north of the country with the south (DK3). The most prominent element in the surrounding landscape is the supermarket, located some 60 m from the monument, as well as the sanitary protection zone, bordering the designed area from the east, and a gas distribution plant, which is approx. 150 m away.

The scope of the project includes: a Calvary route with 14 stations, a project of the “Garden of Eden” and a service section. The pilgrim service zone includes a car park for passenger cars (120 spaces) and coaches (17 spaces) and Pilgrim’s House at the end of the Olive Alley. To get to the Garden of Eden and, at the same time, to the entire premise, we must cross the symbolic Gate of Knowledge of Good and Evil, which introduces us to a world full of biblical symbolism. It includes the Garden of Eden at the entrance to the area where the Tree of Life is designed - the paradise apple tree (*Malus* ‘Royalty’) around which there are stone tablets with the ten commandments of God engraved on them. The garden is filled with a labyrinth of evergreen boxwood, in which delicate spatial forms with Biblical texts from the Old Testament were placed. The main alley - the Way of Life studded with a double row of decorative birch trees (*Betula utilis* ‘Doorenbos’) with snow-white bark leads to the east of the garden. This species, although extremely rarely used in aisle systems, emphasises the main compositional axis, and in the winter, when the leaves fall, its white trunks and branches create an openwork composition, referring to the form of the Gate of the Knowledge of Good and Evil. The way of Life is interwoven with a sinuous path leading to individual stations of the Way of the Cross, referring to the well-known Calvary compositions [12]. The first station of the Way of the Cross is located near the Pilgrim’s House. There are two roads leading to it – one from the Garden of Eden side and the other from the parking lot. The composition of all 14 stations is similar - on the oval square, there are delicate, transparent spatial forms with scenes depicting the passion of Christ. At the foot of the monument, a spring was designed, from which cascade water flows, creating a basin at its base. Then, it turns into a stream and ends its run at the first station of the Way of the Cross. From the places covered by the symbolism of the sacred,

one should also mention the Green Cape Cypress, which is made of 12 cypress trees of the *Chamaecyparis nootkatensis* 'Pendula' species, planted in a circle. *Catalpa bignonioides* 'Aurea' is planted in front of the gazebo, with its beautiful heart-shaped leaves in yellow-green colour.

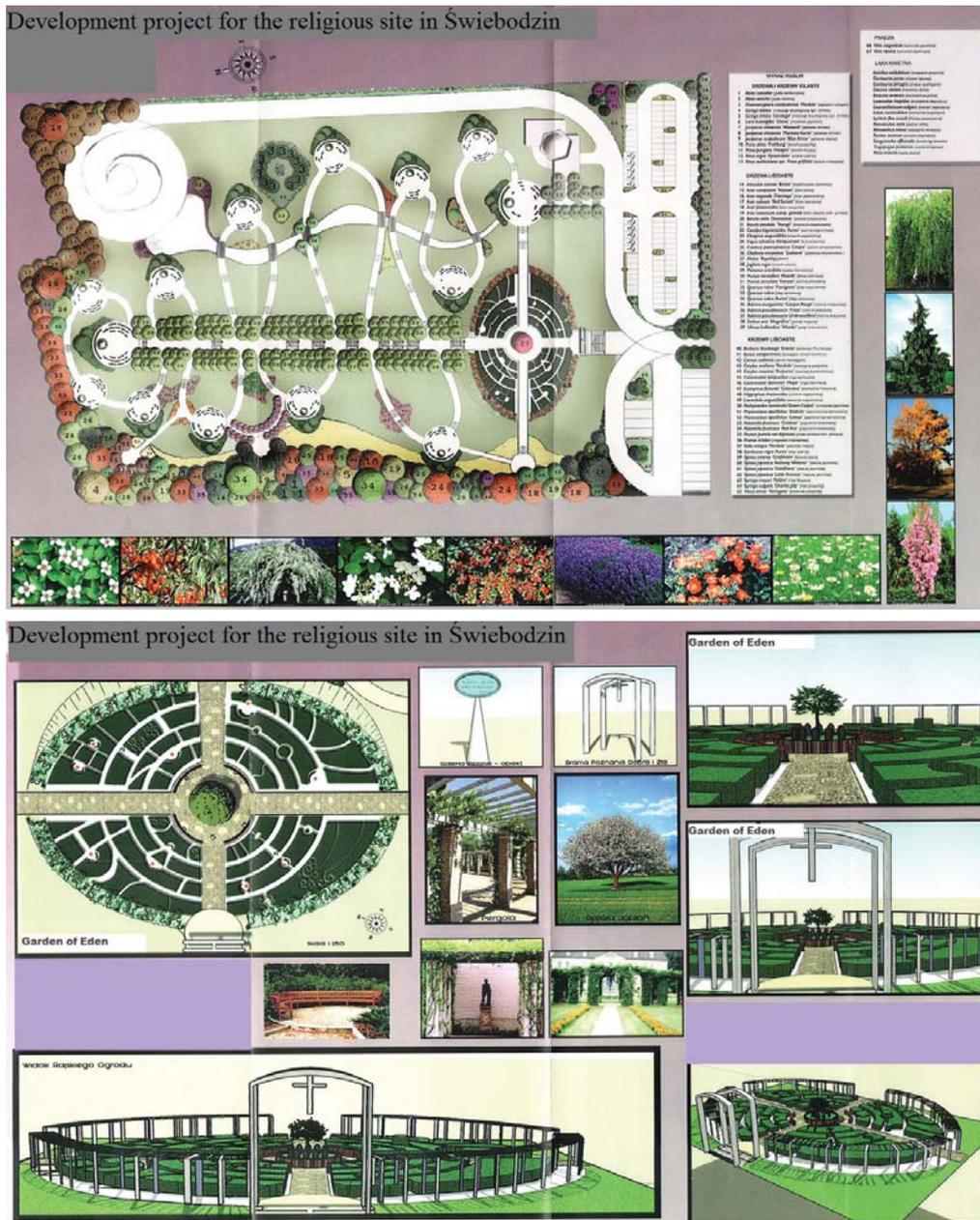


Fig. 5. Development project for the religious site in Świebodzin, M. Śroń under the supervision of M. Rzeszotarska-Palka, ZUT Szczecin 2007 [18]

The whole composition is to symbolise the twelve apostles and Jesus Christ. A cereal field has also been designed – symbolic wheat, which stretches with its gentle arches along the planting at the northern boundary of the area, creating a colourful composition with tree stands.

The design includes the symbolism of the gate, as the border between the sacred zone and the profanum. The gate is the main entrance to the sacred area, and after crossing it, the mystical journey along the Calvary paths, which begins with the passage through the Garden of Eden, starts. In Christian symbolism, the directions of the world correspond to the four gospels. The symbol of the number four appeared in the design of the pilgrimage park in the form of four lodgings in the Garden of Eden, which are to symbolise four evangelists – Matthew, Mark, Luke and John. The cross is a sign of Christianity and a symbol of faith – it serves as a sign identifying the sacred places [8, p. 13]. In turn, the cross was placed at the Gate of Knowledge of Good and Evil, it also creates an arrangement of walking paths in the Garden of Eden. Plants also play an important role in religious symbolism. The tree is the most perfect creation of the vegetable world. Sacred trees are found throughout the history of every religion, in folk myths, in archaeology and art around the world [8, p. 151]. The specific features of a given plant are used to draw analogies between the world of nature and religion [9, p. 256]. Many species of plants with sacred symbolism have been used, including: oak (symbol of strength, faith and perseverance, which leads through the main entrance to the park), olives (symbol of peace, immortality and wisdom – forms the Olive Alley), vines and wheat (sacramental symbolism) and plants at the Calvary road stations: tamarisk, acacia, apple tree, pine, plane tree, boxwood, viburnum and holly (Fig. 5.).

6. Summary

The presented statues of Christ are objects of worship that clearly organise the space, subordinating the functioning of other landscape elements [13, p. 22; 15]. As demonstrated by the analysis of the location of the highest monuments of Christ in the world, the way of managing their immediate environment is most often conditioned by their location. However, in the vast majority of cases, the area around the monument has a representative character, often underlined by the composition of greenery allowing for a proper exhibition of the object in the landscape. The surroundings of the monument of Christ the King in Świebodzin require adjustment to global standards. The comparison of the presented conceptual design with the existing examples from abroad allows us to state that it can be an interesting proposal for the harmonious creation of space around what is currently the world's highest statue of Christ. The composition of the area surrounding the monument, attractive and adapted to the character of the object, would enable its appropriate perception in the landscape [1].

For centuries, people around the world have been trying to mark the place of religious experience (hierophany) commemorating them in a material form: “chapels, roadside crosses in places of accidents, monuments (sometimes as huge as the cross on Giewont, or the statue of Christ in Świebodzin), and even monumental temples” [16, p. 37]. According to Professor Dąbrowska-Budzifłło, religious content has a unique impact on the shape of

the landscape, a “(...) associated cult places were signs with often unmatched clarity” [6, p. 130]. This is also confirmed by the analyses carried out for selected Christ statues located in various places around the world and in different spatial contexts. The influence on the landscape perception of these specific sacral dominants is always significant. However, as the above analyses demonstrated, it is not always enough to give the sacred landscape a symbolic value – even in such a large-scale form, to obtain a beautiful and harmonious space. So, the statement that “raising the landscape to the status of a symbol, allows to obtain space that is not only beautiful, but also significant, expanding the world of human experiences, and thus improving the quality of life” [6, p. 131] must also be conditioned by a carefully thought-out location of the object in a harmoniously shaped environment.

References

- [1] Appleton J., *The experience of landscape*, Wiley, Chichester 1996.
- [2] Bell S., *Elements of visual design in the landscape*, Taylor & Francis, London and New York 2004.
- [3] Bell S., *Landscape: pattern, perception and process*, Routledge, London 2012.
- [4] Boorstein M., *The many meanings of Rio's massive Christ statue*, Washington Post, 09.08.2016, https://www.washingtonpost.com/news/acts-of-faith/wp/2016/08/09/the-many-meanings-of-rios-massive-christ-statue/?utm_term=.26a10f077f92, (access: 15.09.2017).
- [5] Colbert S., *Swiebodzin Jesus To Top Rio's Redeemer Statue*, https://www.huffingtonpost.com/2010/10/29/swiebodzin-jesus-to-top-r_n_775913.html (access: 02.01.2018).
- [6] Dąbrowska-Budziło K., *Symbolika w kształtowaniu i ochronie krajobrazu*, Czasopismo Techniczne, 5-A/2007, 129–131.
- [7] Dąbrowska-Budziło K., *Treść krajobrazu kulturowego w jego kształtowaniu i ochronie*. Wydawnictwo Politechniki Krakowskiej, Kraków 2002.
- [8] Forstner D., *Świat symboliki chrześcijańskiej*, Leksykon, Warszawa 2001.
- [9] Hoffsummer W., *Leksykon dawnych i nowych symboli*, Jedność, Kielce 2001.
- [10] Iverson W.D., *And that's about the size of it: visual magnitude as a measurement of the physical landscape*, *Landscape Journal* 4(1) 1985, 14–22.
- [11] Królikowski J.T., *Widzenie krajobrazu*, [in:] *Sztuka ogrodu – sztuka krajobrazu*, eds. J. Królikowski, E. Kosiacka-Beck, E. Rykała, Vol. 1/2015, 9–12.
- [12] Mitkowska A., *Polskie kalwarie*, Ossolineum, Wrocław-Warszawa-Kraków 2003.
- [13] Myga-Piątek U., *Krajobrazy sakralne i religijne – próba umiejscowienia w typologii krajobrazów kulturowych*, *Sacrum w krajobrazie Prace Komisji Krajobrazu Kulturowego*, Vol. 17/ 2012, 13–23.
- [14] Oleński W., *Czy drapacze chmur mogą być lokalne? Nowa skala krajobrazu Warszawy*, Miejska Pracownia Planowania Przestrzennego i Strategii Rozwoju, <http://www.pracownia-warszawy.pl/strona/pl/artykuly/czy-drapacze-chmur-moga-byc-lokalne-nowa-skala-krajobrazu-warszawy> (access: 03.01.2018).

- [15] Pawłowska K., *Dziwne losy dominant krajobrazowych*, Architektura krajobrazu, Vol. 1–2, 2006, 10–16.
- [16] Plit J., Ślady sacrum w krajobrazie, *Sacrum w krajobrazie Prace Komisji Krajobrazu Kulturowego*, Vol. 17/2012, 33–40.
- [17] Przyłęcki M., *Dominanty w krajobrazie*, Architektura krajobrazu, Vol. 1–2, 2006, 4–9.
- [18] Śroń M., *Projekt zagospodarowania terenu przy obiekcie kultu religijnego w Świebodzinie (Development project for the religious site in Świebodzin)*, diploma thesis under the supervision of M. Rzeszotarska-Pałka, ZUT, Szczecin 2007.
- [19] Wilczak D., *Pomnik Chrystusa Króla, czyli Rio de Świebodzino*, Newsweek, 09.11.2010, <http://www.newsweek.pl/polska/pomnik-chrystusa-krola--czyli-rio-de-swiebodzino,67746,1,1.html> (access: 19.10.2017).

Dorota Wantuch-Matla (dwantuch@up.krakow.pl)

Department of Entrepreneurship and Spatial Management, Institute of Geography,
Pedagogical University of Cracow

MICROSPACES – AN OUTLINE OF TYPOLOGICAL RESEARCH
BASED ON EXAMPLES FROM KRAKOW

MIKROPRZESTRZENIE – ZARYS BADAŃ TYPOLOGICZNYCH
NA PRZYKŁADACH KRAKOWSKICH

Abstract

In the complex systems of urban spaces one can find many places, which, owing to their small scale, are often treated as a part of a larger whole. Whereas their borders are often blurred, their character allows for establishing them as a typological identity. Various “microspaces” play a significant role, often hidden or only temporarily arranged within a specific segment of a city space as its supplement, complement, or simply to make it more attractive. Observation of the transformations taking place in the public spaces of Krakow allows not only for the indication of the fact that such places exist and are being created, it also enables us to frame a sketch of their functional and spatial polymorphism. This article elaborates on some chosen examples of Krakow microspaces and their variants.

Keywords: public urban space, microspaces, urban design

Streszczenie

W złożonych układach przestrzeni miejskiej można odnaleźć wiele miejsc, które ze względu na swoją niewielką skalę bywają traktowane jako składowe większej całości. Tymczasem pomimo nierzadko rozmytych granic ich charakter pozwala na uznanie ich typologicznej odrębności. Różne „mikroprzestrzenie” niekiedy schowane lub tymczasowo aranżowane w obrębie jakiegoś wycinka przestrzeni miejskiej jako jej uzupełnienie, dopełnienie czy dla jej uatrakcyjnienia, odgrywają niebagatelną rolę. Obserwacja przeobrażeń zachodzących w przestrzeniach publicznych Krakowa pozwala nie tylko na wskazanie faktu istnienia i powstawania tego rodzaju miejsc, ale umożliwia także nakreślenie zarysu ich funkcjonalno-przestrzennej wielopostaciowości. W niniejszym artykule omówiono przykłady wybranych krakowskich mikroprzestrzeni oraz ich odmian.

Słowa kluczowe: miejska przestrzeń publiczna, mikroprzestrzenie, projektowanie urbanistyczne

1. Introduction

“Cities attract us, among other reasons, because they offer a chance to find people and places of whose existence we had no idea, as well as we never thought we were willing to find them. A city allows for random social interactions and opens up places where the ideas are born” [15, p. 93].

The landscape of a city is subject to constant more or less substantial, more or less successful changes, permanent or temporary transformations. All of these changes are the reflection and result of a multitude of complex processes that are going on in a city in various areas of its functioning, which creates a ceaseless inspiration for research. Contemporary cities, however, are becoming progressively bigger, more complex and more difficult to grasp not only for the researchers, but primarily for their inhabitants. Quoting Wojciech Kosiński: “The microcosm of the cities on Earth expands like the astronomical universe. The number and contribution of the propositions and polemics about the optimal paradigm of a city of 21st century grows proportionally to the multitude of entities” [9, p. 161]. The accumulation of the themes and their entanglement, as well as a plethora of stimuli, hinder a clear examination of the cities, yet this may be exactly the ingredient which consolidates their urbanity, since a certain randomness and unpredictability of a city life is somehow inscribed into its nature and creates its magnetism. A city examined in a macro scale attracts with a promise of diversity of impressions and opportunities as well as anonymity. Dejan Sudjic writes: “This is the essence of a city: you pick whatever you need and respectfully ignore the rest” [15, p. 94]. A city in a macro scale, however, scares and strains. Hence it appears that the picking referred by Sudjic results from a natural need to reduce the stimuli, to search for a human scale, of more intimate presentations of a city, of “my own” places in a micro scale. This craving evolves along with the city and does not necessarily need to show as a yearning for quarters of intimate cosy houses or narrow medieval streets. It does introduce, however, a respect for traditional urban layouts, and also a search for contemporary methods to domesticate a behemoth and to humanise urban space – or such shaping of it that it would become more accommodating and legible in its complexity, friendlier and easier to grasp with our senses.

2. Microspace

In the last decade, somehow parallel with the fascination with the power of the influence of a city, the interest in returning to what is “closer to the body” has gradually been growing, which is often elusive in the multi-layered assumptions of researches, projects and processes. City microspaces can be found everywhere and totally unexpectedly. Their hallmark is the scale and a certain kind of intimacy, as well as a specific density of stimuli and impressions, which influences the way we interpret a certain piece of space as a concrete place. They can have the features of urban interiors or they can constitute a spatially coherent composition of elements in an open space. They can be new, new-old and old, temporary and permanent. They can appear on various types of minor patches of empty urban plots, in places where once there used to be some buildings but were demolished, in courtyards, in passageways, in subways, on the verge of,

inside or in-between the buildings. They can have a strictly demarcated border or, through their form and character, merely create its intuition. This elusiveness, once it finds a place, does not appear to be anything extraordinary. Manuel de Solà-Morales wrote that a good public space does not have any borders, or the borders it has are non-definable, changeable and complex [14, p. 65]. Yet to grasp the idea of the phenomenon of microspace as a place, one should refer to the most basic notions such as “space” and “place”. As Si-Fu Tuan wrote, there is a strong relationship between them, as people mingle on everyday basis with one and another – owing to this and through the consciousness of space which is synonymous with freedom and adventure, one can appreciate the value of place that offers a certain permanence and a safe haven [17, p.13]. According to Tuan, a closed and humanised space becomes a place, and a place in comparison is “a peaceful centre of established values”. Fencing in, however, is not the precondition for a place to come into being, when considering the aspect of migration and movement in space, it also turns out that a stoppage is experienced as a pause, which allows the transformation of this situation into a place [17, p. 16]. This transformation is easier still, once in this space, we can find with our own senses the elements which give us a sensation of a spatial arrangement of the organisation of the surroundings [17, p. 29]. Jan Gehl writes profusely about project methods in the shaping of durable elements of the surroundings in a manner which allows, or even provokes, a person to stop in a certain place and to entice them to stay there for longer [3, p. 128–196]. But the transformation of a situation into a place may also happen as a result of the influence yielded by temporary or even situational elements. Permanent and ephemeral microspaces may be the points on a psycho-geographic [10, p. 190], in the situationists’ parlance, or to put it differently on a mental city map, where they play a vital role in the social space. The following article presents new, positive examples of microspaces, ones that have a stimulating influence on their users. Yet even a superficial inspection of the surroundings will result in a statement that, amongst the existing microspaces – nooks and corners, there is a considerable number of “evil” places with an oppressive, stress-inducing character.

3. Spaces of consumption and entertainment

For the last couple of years, one can observe an increasing popularity of permanent, seasonal and temporary street bars in Krakow. The so-called Food Trucks have occupied for good a number of fragments of plots in Krakow city centre and beyond. After a couple of years of functioning (even if non-continuous), they have firmly become an inherent part of the city landscape. The culture of eating in the streets (street food) attracts both tourists and inhabitants by combining a variety of taste impressions with a not necessarily that short waiting time, which however can be spent at the pre-arranged nearby tables. The temporary format of *street food* usually entails a provisional character of furnishings around the trailers or food huts. The seats and tables are made of pallets or wooden fruit boxes or plastic bottle boxes. In the summer time, the patrons are protected by parasols attached above the tables and seats, by openwork roofing or awning, there might also appear some decorative elements – platforms, pots with plants, elements of lighting, and on cooler days – heat blowers and blankets. Within



the vicinity of food trucks, especially those long incumbent, not infrequently there appear ambitious artistic murals and graffiti. The attendees of such places are usually young people, yet their temporary transience does not scare the middle-aged nor families with children. Many of such microspaces of temporary character appear in “used” places – e.g. Izaaka square, Dajwór 21, Judah square (Fig. 1a, b, c) which are referred to in literature as *second-hand spaces*, this is due to the shift of focus from their ephemeral existence to another value – namely the recycling of a place. What is important through such a classification, gravity is shifted from temporary impermanence to the ongoing multifaceted evolution of a place [20, p. 264]. Food trucks, camper vans, trailers on wheels, sometimes along with foldable huts and mini kiosks, like an itinerant attraction or a Gypsy camp back from the days gone by, organise the space around and fill in the gaps between the buildings, and sometimes even the gaps on the culinary map of a city. With time some of them, due to their popularity and distinctiveness, become a point of reference to spatial orientation. Their phenomenon consists in a specific duality of their nature, quite common in the present day – they are both a place for social meeting and, as is also characteristic of contemporary shopping galleries, a place for consumption. Although these places are not excessively expensive, visiting them is conditioned by whether the patrons can afford to buy such food and drinks. The amount of time one spends there is noticeably dependent on how much and how long one consumes, to subsequently vacate a place for other customers. Among the food truck places on the map of Krakow, the most numerous are those which occupy a small section of space. There is a notable exception – *Bezogródek Food Truck Park* which is opened in the Spring-Summer season in Piastowska Street (Fig. 1d). The 2,000 square metres of land have been furnished with attractive wooden platforms, green lawns, and even a playground for children. Among them, a dozen or so colourful food trucks are located every year. The most ephemeral types of space connected with the fashion for food truck are events such as e.g. two day’s long Summer Food Truck Festival linked with dancing and open-air cinema, which is arranged in the car park of Imbramowski square.

4. City Beaches

Summer time attractions which have been organised for the last couple of years are city beaches. Taking an example from other European cities such as Paris, Copenhagen, and Vienna, and also from Polish cities such as Warsaw or Wroclaw, year after year Krakow has an increasing number of places where one may feel the atmosphere of a spa health resort. Their small sizes, seasonal composition and character allow for the possibility of examining them in the category of micro-worlds, urban microspaces. Beaches per se do not constitute a novelty – natural, sandy beaches as well as guarded city beaches had been springing up since the beginning of the 19th century and used to be an obvious element of the Vistula landscape and a popular place for summer recreation for the citizens of Krakow. There are quite a few differences, though. First of all, water pollution and also the regulated channel of the Vistula river prevent bathing. Secondly, the mini-beaches apart from giving an opportunity to rest in the sand, offer extensive entertainment with cultural and sports programs: concerts, cultural

events, sports matches, etc. Staying on the beaches is also connected with consumption, as within them temporary facilities are located which serve food and drinks. By the beach near hotel Forum, whose functioning has been temporarily suspended due to administrative reasons, new ones were recently opened: a strip of a beach by Kotlarski bridge (Fig. 1h), a beach near Zwierzyniecki bridge, and also a small and accessible for everybody beach on the premises of the Railway Water Club on Księcia Józefa Street.

5. Playgrounds

The so-called “Children’s’ gardens” [10, p. 23] have an established position in the history and typology of public spaces, and as such, in their own character they could, due to their restricted sizes, functions and character, be treated as a variant of microspace. Recently many playgrounds have been created in the landscape of Krakow. They are known as Dragon Squares and Jordan’s Gardens – one can find better and worse versions, which is conditioned by their more or less lucky location. Meantime in 2016, thanks to an initiative from Archaeological Museum which offered a piece of land for public use, the Archaeological Playground was opened, which looks like a perfect example of a microspace (Fig. 2c). Contrary to uniformly equipped city playgrounds, this place is unique and custom-made for young lads, but also with their caregivers in mind. This place, which is located near the popular Planty footpath, is hidden behind the wall from the side of Straszewskiego Street, yet accessible through a wide-open gate in daytime, thanks to which a visit to this playground is enriched with an additional element of a certain fairy-tale sensation of discovery, of entering a different world of a “Secret Garden”. The leitmotifs of this place are archaeological themes, which refer in a non-obvious manner to the museum exhibits, they form their architectural and spatial re-interpretation, adjusted to the children’s world. The space of the playground, or rather the garden, has been divided into several zones of “functional strips” – a strip of green, of play, of communication and education. The strips have been interwoven with four wooden objects – devices to play which form a slide, a labyrinth, swings and a tunnel. There are also devices resembling musical instruments, climbing walls and a trampoline. Wooden seats, a platform and objects for the youngest of children were also included, as well as a piece of a square devoted to team games and workshops. This composition creates a joyous garden which is multifunctional and multisensory, also spacious and full of cosy “sub-spaces”, nooks and crannies along with being a social meeting place. The equipment of the Archaeological playground, apart from the picturesque white walls of the museum buildings, the whiteness of the surrounding wall, the cast-iron fence, the furnishings predominantly made of wood or covered with it, contributes to the greenery of the ancient trees and the new florae – grass and flowers.

In parallel time, also within the space of Planty park, though from the side of Gertrudy Street, another unconventional playground was opened – the so-called Wild Planty (Fig. 2d). In a place where there used to be an unremarkable tarmac square, a new fairy-tale space was created, where supernaturally sized wooden mushrooms grow, and where reside rocking toys, sound devices and wooden seats.

Another new park and recreation space connected with the playground, which turned a non-place into a place is the so-called Zwierzyniecki Horse Square in Zwierzyniec, next to the Dębnicki bridge. Within this square, new alleys were built, equipped with modern elements of urban furnishings and lighting, as well as devices which can be used in children's games such as colourful wooden animal figures, and a wall game for children which depicts elements from the history of Zwierzyniec.

6. Pocket Parks

The idea of pocket parks has been known worldwide for a couple of decades. This model of a public space has its genesis connected with the investment premium created in 1961 and included in the document *The Zoning Resolution of the City of New York*, so-called bonus/public plaza which allowed the investors building of higher skyscrapers thanks to the creation of tight public spaces (squares, parks) in the city tissue. In the beginning the places which were built on the basis of this document were faced with a wave of criticism, and justly so, as they often were merely empty, concrete squares which were more of a repellent than an attraction – sometimes on purpose, so as not to make their users feel too comfortable with them [11, p. 231]. After years of experience and faced with contemporary challenges connected with the development of a city at the threshold of the 21st century, the documents referring to the “bonus” and, since 2007 the “public plaza”, have been clarified. Also, detailed guidelines referring to the shaping of this kind of space were created [6, pp. 112–113]. Owing to this, within such unique “privately owned public spaces” – as Jerold S. Kayden refers to them in his publication [7], we can find many valuable spots which could successfully be defined as microspaces. A special fame and a status of a model realisation were deservedly earned by New York's Paley Park, designed by Robert Zion and opened in 1967 in Manhattan. Its example perfectly reflects the idea of a space in micro scale and the concept, known all over the world, of place-making, promoted and realised by the New York organisation Project for Public Spaces (PPS) [8, p. 60]. The concept of pocket parks has been popularised all over the world. In the last couple of years in London, within the project, London's Great Outdoors, two million pounds were spent to build them, with a construction of no fewer than a hundred of such places within the space of twenty-six of London boroughs. The idea of pocket parks has also been gaining ground with the authorities of Polish cities since recently. The need and willingness to build such places was declared by the authorities of many cities and in quite a few of them such spaces have been or will be completed, e.g. in Lodz, Wroclaw, Malbork or Krakow, where since 2018, thanks to the initiative of the thriving Municipal Greenery Management and within the project “Gardens for the citizens of Krakow” a building of eighteen pocket parks is scheduled to commence. Ultimately each district should have at least one such park. The concept of pocket parks sparks enthusiasm among the inhabitants and not infrequently it is thanks to them exerting pressure on the actions of city councillors, thanks to their determination and initiative that the subsequent locations are chosen. So far two such pocket parks have been completed on the map of Krakow: “Butterfly Garden” in Dekerta Street in Zabłocie and a square located at the

intersection of Falata and Prusa Streets (Fig. 2a). The Butterfly Garden was created thanks to a collaboration between the students of Jagiellonian University and the Municipal Greenery Management. The whole place with an area of ca. 550 square metres was planted with shrubs and flowers which are particularly liked by butterflies. It was for them also that small wooden boxes were placed. This square is supposed to attract not only butterflies, but also the local inhabitants for whom the wooden seats were built. Local residents were involved both in the concept and realization process of this garden, and the social dimension of this project is emphasised by the fact that the funds for its realisation were partly sourced thanks to social funding. The second of the abovementioned realisations was created in Salwator district. The space of a once neglected square was reclaimed and equipped with wooden chaises lounges, benches, tables, and a pergola, what promptly made this new square popular with inhabitants. Apart from the programme “The Gardens for the Inhabitants of Krakow” other projects are carried out within the city space, whose idea is the utilisation of the potential of places “non-places”, so far defunct, underinvested, yet often ideally located. Among such investments there is, currently almost finished, the Papcio Chmiel Square in Krakow Zwierzyniec (Fig. 2b) or, also still under construction, the linear park in Ruczaj in Zachodnia Street. Both of these places are a perfect example that thanks to good ideas the greenery and an engagingly designed space for meetings, rest and recreation can be arranged on virtually any small piece of land – be it a triangular island between the streets, or a strip dividing acoustic screens and two streets which completely lack expression or a connection with the surroundings.

7. Ephemeral Microspaces

Short-lifespan objects, often connected with various events from the city space, are referred to in *The Metapolis Dictionary of Advanced Architecture* as “impermanences”. According to the dictionary, they are “Non-permanent architectures, linked to a limited space of time after which they disappear (...) These forms of architecture, which establish a limited-time relationship with the landscape, manifest themselves as an event, a proposition which neither remains nor modifies the place it rested once it ceases to exist; it leaves no trace” [3, p. 332]. Their range, character, and their designers’ ideas not infrequently turn such installations into a new place, a point in the space of the city, which can also be referred to using another term from the aforementioned dictionary, namely “reversible” – describing actions whose effects can be turned back and re-established to the original condition which existed before the spatial intervention [3, p. 528]. Within insignificant buildings, small pavilions, urban space arrangements which appear along with cultural, entertainment, artistic and social events, one can often isolate such that bear the traits of a microspace.

Interesting objects and enterprises within the urban space were created in correlation with the Jewish Culture Festival. One of them, the so-called JCF Quarter (Fig. 1e), was described by the organisers of the 25th edition of the Festival as follows: “Quarter is a microcosm – a reflection of the world transferred to smaller, limited space. You live, study, play and rest in a quarter. Quarter needs to include everything for you to be willing to be there” [1]. Within the object various



functionalities could be found: a reading room, a café, a kind of a workshop, and centrally located multifunctional space which, during the festival, was a stage, an extension of the reading room or of the café, and a municipal social salon. Owing to the fact that the structures of the Quarter were built on a green strip between the Old Synagogue and Dajwór Street, the area around it was also used as a cultural and entertainment space, filled in with deckchairs, and thanks to the natural incline as a kind of an amphitheatre. In turn, the 27th JCF included the accomplishment of the project known as the Jewish Boulevard by the Vistula River, near the famous footbridge “Bernatka” (Fig. 1f). On a wide strip of lawn, along the strolling alley and in the neighbourhood of barge-restaurants moored alongside the quay, a sequence of spaces divided by screens with a cultural and recreational character was designed, full of deck chairs, seats, fancy coffee tables, pumped up mattresses and couches, wicker baskets and pots with plants, etc. The screens intensified the impression of a beach, or spa event and comprised various functions: of a café and a temporary reading area – on the one hand, it offered a sensation of intimacy, on the other, thanks to it being made of partly see-through materials, it did not cause a barrier from the outside world. This incomplete, subtle functional and spatial division, in the intention of designers, with its open and changeable structure alluded to the main theme of the festival – layers.

There also was conducted a seasonal, spatial and cultural event that lasted for a couple of months – a campaign “Wyspiański goes to the field” (*which means in local dialect that he goes outside, translators note*), organised on the square opposite the main building of the National Museum in Krakow as part of the programme “Wyspiański’s Year”. This campaign encompassed a temporary installation of a “Graduation Tower” by Robert Kuśmirowski, next to which wooden seats with plant stands were placed (Fig. 1g). The participants of this event, on the inauguration day, would plant flowers and trees of the species inspired by the collection of forty-seven sketches by Wyspiański which presented the pictures of plants, known as the Herbal. Parallel to Wyspiański’s plant stands, the characteristic seats and couches appeared on the museum square, which were presented by Krakow’s partner city – Vienna. This type of furniture, designed by the architects Anna Popelka and Georg Poduschka, which functions with enormous success within the space of the central square of the Viennese Museums Quartier and emphasises its superior role in the system of mutually opening, public spaces which have formed a complex yet functional system [5, p. 40] of the historic quarter since 2003, though with a different colour of the seats every year, which also influences the change in the perception of the furniture per se as well as the surroundings. During this time the geometry and technology of these famous seats changed as well – following the earlier models of “Enzi” and “Endo”, the “Viena” model appeared, and this model was present in Krakow.

8. “DIY” Spaces

Special types of microspaces are those shaped by grass-roots, as they always result from an accumulation of some sort of social and spatial discomfort, and a need of its immediate alleviation. They can be objects, a type of “incidental architecture” [2, p. 418] or an emanation of some kind of shortage and a result of a feeling of necessity to fill in the void [18, pp. 716–

117]. Not infrequently these are modest arrangements and adaptations of some segments of space, which, however, despite meager budgetary expenditures, restore even for some time the dignity to places and to people. In the area of the aforesaid Zablocie, which was controversial owing to the gradually diminishing appeal of its post-industrial heritage confronted with the expansion of housing development as well as the lack of greenness, a park was recently created which was arranged by the employees from the nearby office building. The necessity to have a place to relax, where one could go to have lunch or go for a walk, provoked the makeover of a small enclave of existing yet underdeveloped greenery. Some captured pallets were used to construct temporary seats, an old table was lugged in, swings were made out of old, brightly painted car tires, and colourful festoons were hung between the trees. This place proved to be particularly popular. It also gained media coverage, which drew the attention to such a desperate act which, in a way was this grassroots campaign, thanks to what it triggered a latent public debate about the necessity of creating a park in the Zablocie area.

9. Backyards, Courtyards and Passageways

The places with characteristics of microspaces are to a large extent places which are connected with dwelling, but also with the urban layout of pedestrian communication, and sometimes also with office buildings, services and commercial outlets, or buildings for public institutions. Backyards, courtyards and passageways constitute specific micro-worlds and can have varying status: public, half-private, or private, and their accessibility can be restricted. While focusing the attention on the public ones, one notices that many of them are located in the area of Old City and Kazimierz. The magic and characteristic Mediterranean climate of the Krakow courtyards and passageways is a well-known topic, to mention the beautiful Kazimierz passageway between Izaaka and Józefa streets. While looking at the new constructions one needs to pay attention to a few which are particularly interesting and noteworthy. A kind of a typological hybrid is the space created on the side of the building of the Lesser Poland Garden of Art, which forms a type of a roofed courtyard, of a city salon, square, or even a pocket park and a spatial development of the neighbouring Rajska Street (Fig. 2e). The intimate character of this place, whose interior is shaped by the openwork walls of the building, the greenness, the sophisticated benches and roofing relates with its geometry to the angles of inclination of the surrounding buildings [5, p. 153], and allows being there to be experienced like being in a specific type of a micro-interior city enclave. The impression of interlacing spaces and of blurring of the borders between the exterior of the garden, the streets and the interior of the building is enhanced by the concept of an opening in the openwork covering of the garden from Rajska Street, where the growing crown of the maple tree will fit in the future [19, p. 358].

In the meantime, additional public space was created, connected with another cultural edifice – The Józef Czapski Pavilion built in 2016 (Fig. 2f). This is a type of a courtyard available during the opening hours of the museum. The green courtyard, hidden at the back of the buildings in Piłsudskiego Street, like other examples of microspaces gives the impression of a city oasis. It makes a type of a foreground to take in the whole picture of the museum, and

in large part, it is covered with a lawn with a subtle, elegant access to the exit zone from the pavilion, and even more subtly delineated “path” to the café patio at the foot of the building.

Due to the still existing fashion to build gated communities in Krakow, one will not find too many public and structurally interesting new backyards or passageways connected with housing estates. There is one noteworthy example of a passageway, though – the one located in Zablocie which connects Ślusarska and Tadeusza Romanowicza Streets (Fig. 2g,h). This link built by a property developer as part of a project of a huge housing estate stands out as an attempt to make it “a place to stop” [4, p. 128]. This passageway, apart from catering for the foot traffic, is enhanced with greenery, as well as with the specifically designed elements of small architecture which invite for the children games and exercise no matter how old you are. Within the space of the passageway walls with holes were build, which allow one to sit in them or walk through them, seats with varying height, a kind of pirate grass, and in the surface of the passageway and elsewhere there are spots for backyard games, such as shove-halfpenny or bottle-caps. Another added value of this place is the fact that on the wall which stretches on the south side of the passageway, which fences it from the plot settled by Museum of Contemporary Art in Krakow, there is a mural by the artist Piotr Lutyński.

10. Summary and Conclusions

The microspaces discussed in this article have been divided with regard to the functions which they have in a city and in the structure of its public spaces and also with relation to the criteria of their durability. The typological taxonomy proposed by the author forms a research stage and has an open nature, which allows for further exploration of this issue, and for the territorial extension of the range of research and for the addition of subsequent variants. At the current stage of research, the observation and analysis of the features and functions of the chosen examples of microspaces allow for the following conclusions:

- ▶ microspaces can be characterised as permanent or temporary,
- ▶ they can have various functions: recreational, for communication, social (meeting places), cultural and connected with consumption,
- ▶ their characteristic feature is the micro-scale size compared to the city scale, intimacy and a sensation of a density of stimuli and spatial elements, which influence our interpretation of a given piece of space as a specific place,
- ▶ they can be a product of adaptation work – grassroots, social, informal, or a realisation of a specific, professional project,
- ▶ they can have the characteristics of an urban interior or they can form a spatially coherent composition of elements in an open space,
- ▶ they can have a strictly delineated border, or merely create an intuition of it by their character and form,
- ▶ this article included microspaces of public status (e.g. pocket parks) or private but open to the public (e.g. plots with street food) and public-private (e.g. beaches administered by private companies),

- ▶ microspaces can be accessible round the clock or their access may be restricted by opening hours (e.g. the Archaeological Playground are closed at night), and also by entrance charges (e.g. open-air cinema),
- ▶ they can be positively stimulating or oppressive (e.g. neglected and dangerous dark alleys).

References

- [1] Festiwal Kultury Żydowskiej, <http://www.jewishfestival.pl/pl/kwartal-fkz> (access: 12.12.2017).
- [2] Feuerstein G., *Tezy na temat architektury incydentalnej*, [in:] *Przewodnik dla dryfujących. Antologia sytuacjonistycznych tekstów o mieście*, eds. transl. Kwaterko M., Krzaczkowski P., Bęc Zmiana, Warszawa 2016, 418–422.
- [3] Gehl J., *Życie między budynkami. Użytkowanie przestrzeni publicznych*, RAM, Kraków 2009.
- [4] Gyurkovich M., *Hybrydowe przestrzenie kultury we współczesnym mieście europejskim*, Monografia 438, seria Architektura, Politechnika Krakowska, Kraków 2014.
- [5] Gyurkovich M., *MuseumsQuartier jako dopełnienie kompozycyjne Forum Cesarskiego w Wiedniu*, *Wiadomości konserwatorskie – Journal of Heritage Conservation*, 29/2011, Zarząd Główny Stowarzyszenia Konserwatorów Zabytków, Warszawa 2011, 34–41.
- [6] Jopek D., *Wpływ lokalnych przepisów prawnych na kształtowanie przestrzeni i krajobrazu miejskiego Nowego Jorku*, Ph.D. Thesis, Kraków 2014.
- [7] Kayden J.S., *Privately Owned Public Space: The New York Experience*, John Wiley, New York 2000.
- [8] Kosiński W., *Dobro i piękno – miejsca przyjazne człowiekowi w miastach modernizmu po 1945: idee, projekty, realizacje*, *Przestrzeń i Forma*, 20/2013, Wydawnictwo Uczelniane Zachodniopomorskiego Uniwersytetu Technologicznego w Szczecinie, Szczecin 2013, 35–94.
- [9] Kosiński W., *Paradygmat miasta 21 wieku*, Politechnika Krakowska, Kraków 2016.
- [10] Łakomy K., *Ogrody w krajobrazach miast (cz. 2, od XVIII do XX w.)*, *Czasopismo Techniczne*, 6-A/2012, 17–26.
- [11] Montgomery Ch., *Miasta szczęśliwe*, Wysoki Zamek, Kraków 2015.
- [12] Pluta K., *Przestrzenie publiczne miast europejskich. Projektowanie urbanistyczne*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2012.
- [13] *Przewodnik dla dryfujących. Antologia sytuacjonistycznych tekstów o mieście*, eds. transl. M. Kwaterko, P. Krzaczkowski, Bęc Zmiana, Warszawa 2016.
- [14] Solà-Morales M. de, *The Impossible Project for Public Space*, [in:] *In Favor of Public Space. Ten Years of the European Prize for Urban Public Space*, Centre de Cultura Contemporània de Barcelona and ACTAR, Barcelona 2010, 25–28.
- [15] Sudjic D., *Język miast, Karakter*, Kraków 2016.
- [16] *The Metapolis Dictionary of Advanced Architecture. City, Technology and Society in the Information Age*, eds. M. Gausa, V. Guallart et al., Actar, Barcelona 2003.

- [17] Tuan S.F., *Przestrzeń i miejsce*, Państwowy Instytut Wydawniczy, Warszawa 1987.
- [18] Wantuch-Matla D., *Micro-spatial and urban ephemera: bottom-up and temporary initiatives in public space*, [in:] *Virtual City and Territory. "Back to the Sense of the City: International Monograph Book"*, Centre de Política de Sòl i Valoracions, Barcelona 2016, 712–722.
- [19] Wantuch-Matla D., *Przeobrażenia miejskich przestrzeni publicznych w Polsce a fundusze europejskie – województwo europejskie/Public space transformations in Poland and European funds – Lesser Poland Voivodeship*, TeKa Komisji Urbanistyki i Architektury, PAN o/Kraków, Vol. XLV, PAN, Kraków 2017, 353–366.
- [20] Ziehl M., Oßwald S., *Practices in second hand spaces: Producing value from vacancy, Ephemera. Theory & Politics in Organisation* [online magazin], Vol. 15(1), Ephemera editorial collective, 2015, 263–276, www.ephemeraweb.org (access: 22.11.2017).



Fig. 1. a) Izaaka Square, b) Dajwór 21 Street, c) Judah Square, d) Bezogródek Food Trucks, e) JCF Quarter, f) Jewish Boulevard by Bernatka Bridge, g) “Wyspiański goes to the field”, h) Urban beach by Kotlarski Bridge (Photos a, b, c, f, g – D. Wantuch-Matla; d – J. Matla; e – courtesy of BudCud)



Fig. 2. a) Pocket Garden at Falata/Prusa Streets, b) Papiro Chmiel Square – pocket garden, c) Archaeological Playground, d) Wild Planty Playground, e) Lesser Poland Garden of Art, f) Józef Czapki Pavilion courtyard, g) Passageway at Ślusarska/Romanowicza Streets (Photos: a, b, e, f, g, h – D. Wantuch-Matla; c, d – J. Matla).

Krystian Leski

Przemysław Luty

Andrzej Łucki

Dawid Jankowski (jankowski@indy.chemia.pk.edu.pl)

Chair of Chemical and Process Engineering, Faculty of Chemical Engineering
and Technology, Cracow University of Technology

APPLICATION OF CIRCULATING FLUIDIZED BED BOILERS IN THE FUEL COMBUSTION PROCESS

ZASTOSOWANIE KOTŁÓW Z CYRKULACYJNĄ WARSTWĄ FLUIDALNĄ W PROCESIE SPALANIA PALIW

Abstract

The combustion of fuels plays an important role in the field of industry and power engineering. Nowadays, a lot is being done to reduce the industry's interference in the environment, due to ecological considerations. Not only is the fluid technology environmentally friendly, but also it is a convenient method of energy production from wide range of fuels. The article presents a summary of the most significant events in the history of fluidized bed boilers, there is also a description of construction and operation of a circulating fluidized bed boiler and its comparison with technologically similar bubbling fluidized bed boiler. The usage of diverse types of fuels is discussed and compared. Special emphasis is placed on the application of fluidized bed boilers in Polish industry.

Keywords: fluidized bed, combustion, circulating fluidized bed boiler, CFB boiler

Streszczenie

Spalanie paliw odgrywa ważną rolę w dziedzinach przemysłu i inżynierii energetycznej. Obecnie, dokonuje się wielu starań, mających na celu zmniejszenie wpływu przemysłu na środowisko, ze względu na względy ekologiczne. Technologia fluidalna jest nie tylko przyjazna środowisku, ale także jest dogodną metodą produkcji energii z szerokiej gamy paliw. Artykuł przedstawia kilka najważniejszych wydarzeń historycznych, które przyczyniły się do rozwoju technologii fluidalnej. Umieszczono w nim opis konstrukcji i działania kotła z cyrkulacyjną warstwą fluidalną, a także jego porównanie z podobnym pod względem technologicznym kotłem z bąbelkową warstwą fluidalną. Opisane i porównane jest użycie różnych typów paliw. Szczególny nacisk położony jest na użycie kotłów fluidyzacyjnych w polskim przemyśle.

Słowa kluczowe: złoża fluidalne, warstwa fluidalna, spalanie, kocioł z cyrkulacyjną warstwą fluidalną, kocioł CFB

1. Introduction

Along with the development of technology, many innovative fuel combustion methods have been developed in power boilers. An important role is played by fluidized bed boilers, which due to the structure of the fluidized bed can be divided into bubbling fluidized bed boilers (BFB) and circulating fluidized bed boilers (CFB).

Fluidized bed boilers are devices for direct conversion of chemical energy contained in fuel for thermal energy. Indirectly from the generated hot steam electricity can be generated. These boilers do not have a complicated construction. The basic construction element is the sieve bottom, under which a fluidizing agent, e.g. air, is fed. Apart from fuel, the bed can also be built from inert material (eg quartz sand or chamotte), which allows maintenance favorable process conditions, such as, for example, increasing the combustion surface, isothermality of the bed, good mixing of fuel and oxidant [1].

The use of fluid combustion technology brings many benefits. First of all, the emission of dinitrogen oxide to the atmosphere is significantly reduced due to the low temperature in a fluidized bed chamber (about 860°C) [2]. Moreover, thanks to the addition to the fluidized bed sorbent binding sulphur from fuel, one can note a reduction emitted to the atmosphere sulphur oxides. The sorbent is usually ground limestone. In fluidized bed combustion, the fuel particles are intensely mixed with the oxidant, which makes it possible reducing the size of the combustion chamber itself. This technology also allows for the combustion of low-quality fuels with a simplified carburizing system [3].

For the first time, the fluidization process was observed in 1921, when German chemist Fritz Winkler introduced gas combustion products into the bottom of the crucible in which the coke particles were found. He observed then an intense process of lifting particles through a flowing gas that resembled boiling water liquid. The year 1939 brought another discovery - two scientists from the Massachusetts Institute of Technology then tried to find the right contacting process for the solid phase and gas to perform catalytic cracking. That's how the new discovery came about phenomenon – fluidization in the circulating layer. Since then, this technique has begun to develop dynamically in the petrochemical industry. In the sixties fluidized combustion in the bubbling layer was investigated [2]. Currently, a huge share of fluidized bed boilers are used on the Asian continent.

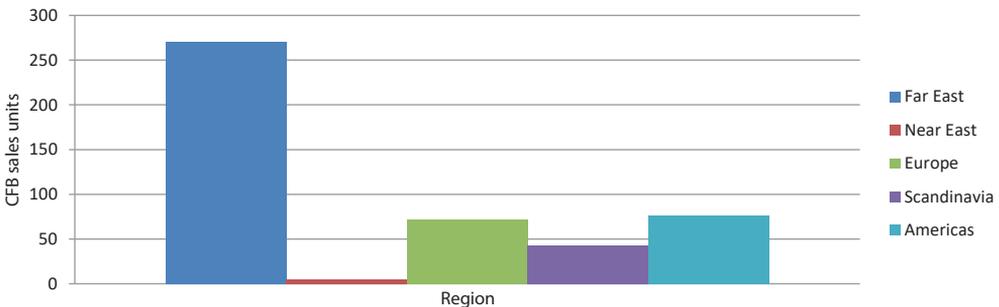


Fig. 1. Sales of CFB boilers by Amec Foster Wheeler until 2015 [4]

The growing interest in CFB technology resulted in the 60s discovery that it is suitable for carrying out operations with powdered solids and at high speeds. The method was developed for calcination of aluminium, which soon came into common use. The first CFB boiler designed to generate steam and heat was built in 1982. It was a revolutionary event in the field of energy, and this technology still exists and is dynamically developing [2]. Compared to CFB technology, BFB technology is currently much less common, as evidenced by the list of installed by Finnish heating companies in the form of CFB and BFB boilers (Fig. 2).

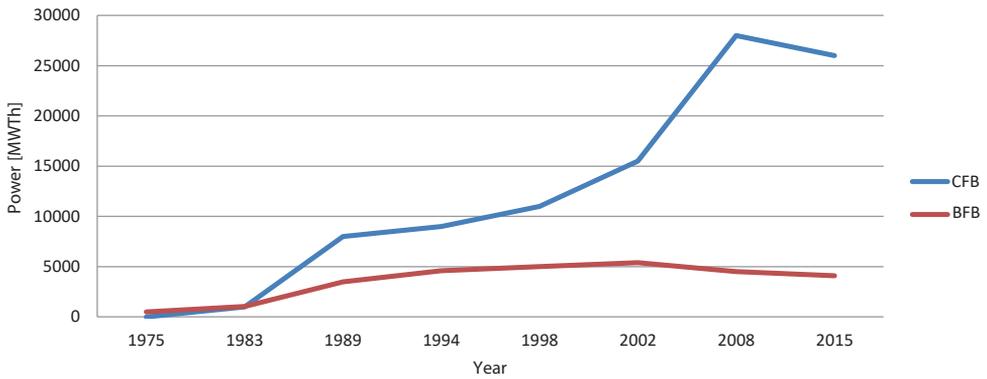


Fig. 2. Installed thermal power of CFB and BFB boilers in the years 1975–2015 [5]

Analysis and broadening of knowledge in the field of fuel combustion in fluidized bed boilers, and especially in boilers with a circulating fluidized bed, can reduce costs combustion and improve the quality of the atmosphere. Air on earth at the turn of recent years it is becoming worse and worse quality, among others due to exceeding the content toxic dusts and chemical compounds emitted, among others from a combined heat and power plant, traditional coal stoves, or factories. It is observed in the United States significant reduction of harmful gas emissions as a result of pro-ecological implementation solutions in the energy sector (Fig. 3).

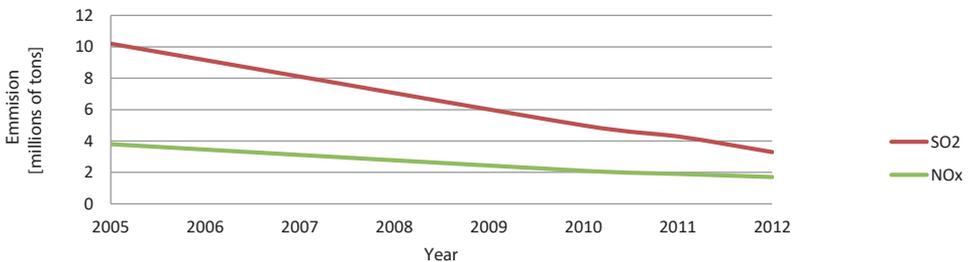


Fig. 3. Emission of sulphur dioxide and nitrogen oxides in the electricity sector in the USA [5]

2. Fluid combustion

2.1. Circulating fluidized bed (CFB)

An example diagram of an installation for burning solid fuels using CFB technology is shown in Figure 4. The fluidized bed combustion process starts with transporting the fuel with a screw conveyor (1) to CFB reactor (2). In the lower part of the reactor for the under-sieve chamber (3), a continuous air stream is fed (4) to ensure adequate turbulence and circulation of the bed in the camera. The fluidizing agent is preheated in a heat recuperator (5) to temperatures around 350°C by waste gases. In addition, when starting up the reactor or if the process requires it, the air can be additionally heated in the pre-heater (6) before introduction to the chamber. Secondary air (7) is fed after the cyclone. The off-gas after leaving the reactor is transported to the cyclone (8), where its purification with solid particles (ash, fluidized bed material) takes place. The gas then goes to the wet cleaning chamber (9) and the heat exchanger (5). In the last phase of the process, the exhaust gases are tested for the content of such gases chemical components, such as heavy metals or dioxins. Depending on the results of the quantitative and qualitative analysis of the flue gas can be directed to the installation purification or be introduced directly into the atmosphere [6].

Furnace ash, so-called ashes from the bed are removed from the bottom reactor connection (10). In this ash, there are no sinters or fused silica (glass), however, there are gypsum, calcium oxide and other amorphous ingredients [7].

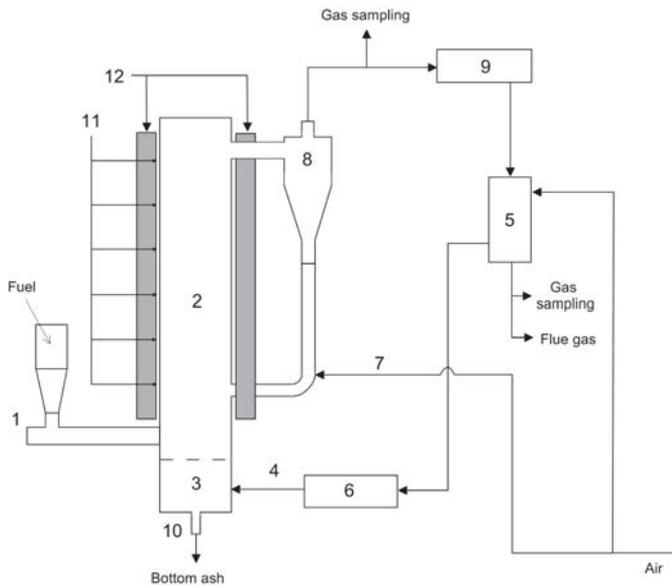


Fig. 4. Installation diagram using a circulating fluidized bed (CFB) [6]

- 1 – screw feeder, 2 – CFB reactor, 3 – sieve chamber, 4 – stream of air, 5 – heat exchanger, 6 – heater, 7 – secondary air, 8 – cyclone, 9 – wet chamber flue gas cleaning, 10 – spigot, 11 – thermocouples, 12 – electrically heated modules

The reactor contains thermocouples (11) that are used for measurement inside the reactor, at different heights. For temperature control ignition and start-up of the reactor, before it reaches its nominal operating parameters, there are electric heating modules installed (12) [7].

The main carrier of dioxins, heavy metals and other undesirable chemical compounds generated by fluidized bed combustion are fly ash contained in waste gases leaving the CFB reactor. These contaminants follow the pattern later they get to the exhaust gas, where their number is calculated as given below pattern [9]:

$$c_{1,i} = \frac{Ash}{2V_{fg}} c_{0,i}$$

where:

$c_{1,i}$ – dioxins/heavy metals content in exhaust gas [mg/Nm³]

Ash – ash content in solid fuel

V_{fg} – volume of fumes per kilogram of solid fuel [Nm³/kg]

$c_{0,i}$ – initial content of dioxins/heavy metals in solid fuel [mg/kg]

2.2. Comparison of a circulating fluidized bed with a bubbling fluidized bed

The first used fluidized bed boilers were bubbling fluidized bed boilers (BFB). Their action is based on the fact that under the influence of air flowing through the fuel layer, gas bubbles appear in the bed particles of fuel, ash or sorbent. The deposit in this case will not circulate in the boiler space, as is the case in CFB boilers [9]. Both of these fluidized bed combustion techniques differ in min. thermal load, the amount of sorbent used, additional equipment (Tab. 1). In CFB boilers it is necessary to use larger fluidizing velocity compared to a stationary bed. CFB technology allows for the construction of power boilers with much higher powers than in the case of BFB.

A limitation in increasing the energy efficiency of CFB boilers remains the strength of construction materials for process conditions.

Table 1. Comparison of CFB and BFB combustion techniques [3, 7]

| Parameter CFB | | Boiler type | |
|---|---|-------------|------------------|
| | | CFB | BFB |
| Thermal load | q_A [MV/m ²] ¹ | 1.8–2.5 | 1.2–1.5 |
| | q_V [MV/m ³] ² | 0.2–0.4 | 0.1–0.2 |
| Average size of fuel particles [mm] | | 3-30 | < 25 |
| Power [MW _{th}] | | >50 | <50 |
| Air speed [m/s] | | 5–9 | 1–3 |
| Burning temperature [°C] | | 850–900 | 850 |
| The surface of the deposit | | unspecified | strictly defined |
| Ca/S | | 1.5 | 2.5–3.5 |
| The influence of the bed height on binding of SO ₂ | | no | yes |

¹ thermal load related to the surface,

² thermal load related to the volume.

2.3. Costs of fluidized bed combustion

Fluidized bed combustion has many benefits, but it is worth knowing whether investing in such processes also brings financial benefits. Demand for capital for the construction of a fluidized-bed plant at power 200,000 t/a is about 54,500,000 €. These costs include, for example: land development, equipment costs, boiler, steam generator, turbogenerator and other construction costs and capital costs. These amounts, however, are located in the same range as in the case of grate combustion.

The use of fluid combustion is known for the fact that there is no need to instal equipment for removing nitrogen oxides from flue gases. However, the risk increases corrosion and related costs of equipment renovation and repairs [13].

3. Combustion of fuels in CFB boilers

3.1. Petroleum coke

The main task of the petrochemical industry is oil refining to petroleum coke. In recent years the production of this substance has increased significantly, which is a clear threat to the environment, due to the high sulphur content in this product. The use of petroleum coke as a raw material for the metallurgical industry is not advisable, a much better method is use of coke as fuel.

Combustion of coke in pulverized boilers, however, may cause excessive sulphur oxide emissions to the atmosphere. However, the use of a circulating fluidized bed boiler ensures reduction of pollutant emissions by binding sulphur in the bed. A deposit containing limestone then binds the sulphur, the product of which is calcium sulphate [2].

In the case of burning of petroleum coke, the most important thing is to adopt appropriate operating parameters. Pilot studies on emissions of sulphur dioxide to the atmosphere showed that its concentration in the flue gas decreases almost linearly with an increase in the excess air ratio and the calcium to sulphur ratio (Ca/S). In addition, the temperature of approx. 850°C

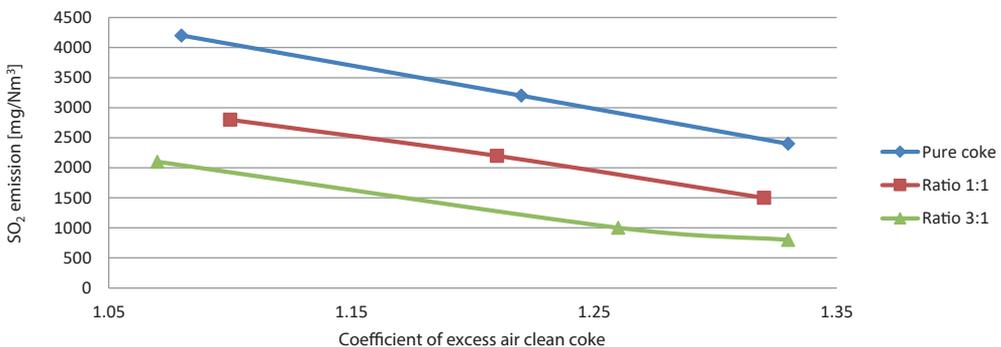


Fig. 5. SO₂ emission to the atmosphere as a function of the excess air ratio [10]

is the optimum temperature for sulphur retention. The values slightly differ from each other, depending on the ratio of carbon to coke (Fig. 5).

In a circulating fluidized bed, the main technical problem is heavy metal oil coke escaping into the melting ash. Despite the fact that coke has relatively low ash content, elements such as vanadium or nickel penetrating there form molten ash compounds that cause problems with agglomeration in the combustion chamber or in the circulating fluidized bed. Agglomeration takes place under the effect of fluidized bed temperature, fluidization velocity, material concentrations in the exhaust gases and the temperature of the walls of the heating surfaces. A relatively high fluidization velocity and material concentration will be conducive to the prevention of agglomeration [10].

There are two main types of erosion caused by different substances. The first of these is high-temperature erosion with strong links to agglomeration, as it is caused by heavy metals. In high temperature conditions ($> 590^{\circ}\text{C}$) molten ash compounds are formed that can react with sulphur to form complexes with a low melting point and contributing to erosion. The second type of erosion is erosion caused by SO_2 , which occurs if no limestone is added to the boiler. In the temperature range $850\text{--}950^{\circ}\text{C}$ and with the addition of sorbent, you can easily reduce this phenomenon. Temperature control in the boiler allows the impact of agglomeration and erosion to be limited [10].

3.2. Coal and granules made of rice straw

In addition to conventional methods of obtaining energy, consisting of burning fossil fuels, such as coal, oil or natural gas, waste incineration is also used (including industrial, municipal, agricultural). These methods are gaining increasing popularity, due to the usually low costs of obtaining raw materials energy. An example of an installation using both conventional and agricultural fuels, as well as innovative, is a boiler with a circulating fluidized bed, used for combustion a mixture of coal and granules from rice straw, where sand is used as a bed silica [11].

The use of rice straw as a fuel is strictly determined by areas the presence of this plant. The most profitable is for countries where this plant is common - these are Asian countries, such as China, Thailand, Vietnam, India or Japan. If the above-mentioned installation is used, it occurs to lower the average temperature of the deposit due to the presence of rice straw in the fuel. A lower bed temperature, the effect of reducing emissions of nitrogen oxides NO_x and dioxide SO_2 sulphur, however, carbon monoxide CO emissions are increased.

The combustion efficiency after adding the granulate to the coal decreases slightly by adding 25% of the mass granules, the yield is reduced by less than 0.5%. At the presence of 50% by mass of straw granules, this efficiency drops by about 1%, whereby in each case, it is not less than 98.5% of pure combustion efficiency coal.

Conducting the above-described process is economically justified and in many countries, allows you to get rid of agricultural waste, contributes to the reduction of oxides nitrogen and sulphur oxide. The only disadvantages appear to be a slightly higher emission of carbon monoxide and minimal decrease in combustion efficiency.

3.3. Coal combustion in fluidized bed boilers

Although the fluidization phenomenon will soon be celebrating its 100th anniversary discoveries, in the professional power engineering the first boilers with fluidization furnaces appeared in the 1960s. Dynamic growth in this type of solutions may be observed over the last twenty-five years, when the block energy with fluidization furnaces began to achieve thermal efficiency comparable to other systems (Tab. 2) and developed in societies' larger environmental awareness. For the users of this type of solution, it turned out to be valuable potential to reduce emissions of SO₂ and NO_x, but also the opportunity to use fuel solid and liquid of low quality [15].

Combustion of fossil fuels in fluidized bed boilers brings many benefits, such as reducing harmful emissions or increasing combustion efficiency [11]. This feature is particularly important in the case of coal combustion, which is usually a heavily contaminated material (Tab. 3). Coal occurring in the USA contains on average from 0.5% to 5% of sulphur in its composition [12]. Because of its presence, sulphur compounds, mainly sulphur dioxide, get into the atmosphere from burnt coal is the main cause of the formation of acid rain (due to the formation of acid sulphate after dissolving this oxide in water). In addition to sulphur dioxide, to the atmosphere small amounts of sulphur dioxide are also emitted, which forms with water sulphuric acid [13]. These compounds have a negative impact on the environment, and often on industrial equipment due to the potential for the formation of acidic substances. This often brings with it the need to use more expensive materials, such as permanently resistant to corrosion.

It is common practice in the combustion of fuels to use clean for this purpose oxygen instead of air. This technology has many advantages, such as reducing the quantity impurities entering the boiler, reduction of emissions of sulphur oxides, carbon and nitrogen, or also the leveling of unburnt carbon in fly ash [14].

Table 2. Comparison of thermal efficiency and investment outlays of energy blocks [15]

| Energy blocks | Capital expenditures, EUR90/MW | | | Thermal efficiency in % | | |
|--|--------------------------------|------|------|-------------------------|------|------|
| | 1995 | 2010 | 2020 | 1995 | 2010 | 2020 |
| Combined circuit with gas turbine (GTCC) | 559 | 550 | 528 | 55 | 60 | 62 |
| Steam-gas system with gassing (IGCC) | 1661 | 1552 | 1333 | 46 | 49 | 50 |
| Fluidized bed furnaces | 1249 | 1179 | 1040 | 44 | 45 | 47 |
| Supercritical | 1336 | 1262 | 1114 | 44 | 48 | 51 |
| Fuel cells | 1828 | 1128 | 820 | 61 | 66 | 71 |

Table 3. The content of some elements in selected samples of solid fuels [14]

| Raw | % by weight | | | | |
|------------------------|-------------|------|------|------|------|
| | C | H | O | N | S |
| American coal | 67.42 | 4.14 | 7.98 | 1.04 | 3.05 |
| Chinese coal | 65.00 | 3.85 | 9.95 | 0.76 | 0.50 |
| Chinese petroleum coke | 88.56 | 3.53 | 0.14 | 1.06 | 4.31 |

Table 4. Emission of harmful substances for the CFB boiler at EC Katowice [15]

| Compound | Guaranteed emission [mg/Nm ³] | Measurement [mg/Nm ³] |
|-----------------|---|-----------------------------------|
| SO ₂ | 540 | 417 |
| NO _x | 460 | 155 |
| CO | 200 | 52 |
| Dust | 50 | 8.3 |

The combination of several pro-ecological solutions in the field of fuel combustion gives measurable benefits. Particular emphasis on the implementation of these solutions should put countries having large natural carbon deposits and deriving energy to a large extent from it, in particular, USA, Russia, Australia and China. It is not without reason that the dynamic development of CFB technology is observed in China, where coal resources are very large, and the population in this country is over 1.3 billion.

3.3.1. The use of fluidized bed boilers in the Polish power industry

In Poland, the first fluidized bed boiler was put into service in 1997 in Bielsko-Biala Heat and Power Plant and since then you can observe a regular replacement of boilers in power plants in various regions of the country. In 2000, a new fluidized bed boiler was commissioned at EC Katowice CFB construction, which in addition to the combustion of the basic fuel in the form of carbon. It is also intended to incinerate waste in the form of post-flotation silt coal. The boiler used is a single-boiler boiler with a furnace atmospheric and natural water circulation. Fluidized bed combustion takes place at a temperature of 850-900°C. The circulating bed material is formed of ash resulting from the combustion of fuel, sand and limestone, which is used for capturing the sulphur released in the combustion process. Sand is used only during the boiler start-up to create a preliminary bed layer to allow start burning solid fuel. Low combustion temperature in the boiler with circulating fluidized bed is the optimal temperature for dry flue gas desulphurization using limestone. The combustion technology in the circulating fluidized bed ensures very low emissions of harmful substances without additional construction external installations (Tab. 4) [16].

One of the most spectacular examples on a global scale is the use of fluidized bed boiler in power industry is putting into use in 2009 a block power plant with 460 MW power at the Łagisza power plant in Będzin. This is the first on the world's energy block which is completely based on fluid technology and simultaneously having supercritical parameters, and at the same time it is the largest fluidized bed boiler. The fuel used is hard coal and coal-derived waste, mainly coal sludge. The block replaced five retired small units (3 x 120 MW and 2 x 50 MW) significantly increasing the efficiency of production and reducing global dust and gas emissions. As a result, the burden of environmental pollution has been reduced and economic efficiency increased. The efficiency of existing blocks at the Łagisza power plant was around 35–36 percent, and the new block achieved 45 percent. This significant difference is primarily due to the supercritical parameters and better efficiency of the whole circulation [17].

Supercritical parameters mean that there is such a high pressure that it minimises the difference in density between steam and water. Above the critical point of balance thermodynamic is the phase that does not determine whether it is steam or water at temperature 560°C and a pressure of 275 bar. These are the parameters above which the water only occurs in the gas state. After the pressure increase, you cannot condense steam. Fluidized bed boilers are a better solution for supercritical parameters, because thermal loads in the combustion chamber on the fuel side they are smaller than in dust boilers, working conditions and stress risk are also more favourable. Emission requirements for Łagisza comply with the European Union Directive for Large Combustion Installations (Large Combustion Plants). The emission of sulphur dioxide is controlled by adding limestone to the furnace. The emission of nitric oxide is controlled by the process gradual combustion and its relatively low temperature, while dust emission it is controlled by an electrostatic precipitator. The boiler is also equipped with installations supporting devices such as the ammonia water injection system (SNCR) [10,22].

3.4. Waste incineration in fluidized bed boilers

In 2015, a total of 142 million tonnes of waste was generated in Poland, of which 8% (11 million tonnes) were municipal waste, and 92%, or 131 million tonnes, other than utility waste. The main source of the latter, as in previous years is mining and extraction, which constitutes approx. 53% of total waste. The yearly amount of municipal waste produced by enterprises and households increases by around 5% per annum and in 2015 one inhabitant of Poland accounted for about 280 kilos of rubbish production per year.

In Poland, the basic method of waste management is storage, from the data presented in the 2016 GUS report, it appears that in this way 44% of their total quantity was neutralized and 26% recycled. Only 13% municipal waste generated in Poland has been disposed of in trash incinerators, which makes the result more than twice lower than the European average (Fig. 6) [19].

Separated energy fractions from municipal waste (biomass, plastics) are a source of alternative fuel (RDF) production and clean thermal energy. Secondary segregation allows,

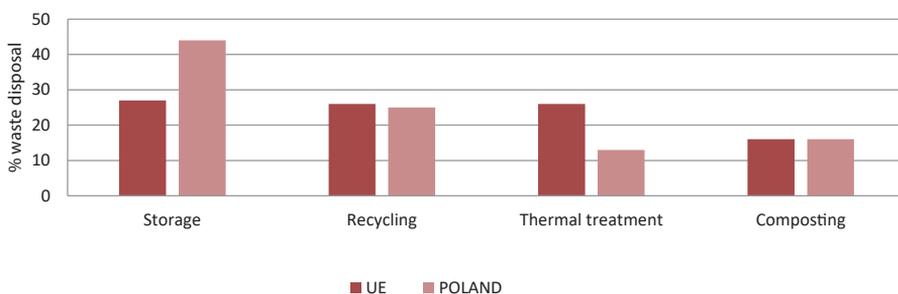


Fig. 6. Methods of disposal of municipal waste in the EU and Poland in 2015 [19]

on the one hand, recovery of recyclable materials and recycling for production. On the other hand, mixed materials can be used to obtain materials producing alternative fuel in the form of briquettes and pellets. In this regard, significant progress has been made on the candles, including fluidized bed incinerators where alternative fuels are burnt are becoming more and more popular.

There are over 470 municipal waste incineration plants in Europe. In Poland at present, there are 6 municipal waste incineration plants, and another 4 are planned or are under construction. In the domestic thermal processing of waste none of the incinerators use CFB boilers, but this technology is being successfully used in Europe and worldwide. One of the newest alternative fuel fired power plants is in Lomellina (Italy), processing 200 thousand Mg/year of municipal waste. The cost of its construction amounted to EUR 130 million, and 17 MWe power has been obtained. The plant has three technological lines separating municipal waste into fractions depending on the size of the fuel particles and their enriching substances. Alternative fuel obtained in the amount of 60% of recycled municipal waste, has a calorific value of 10.5 to 17 MJ/kg. In the combustion process RDF produces 7% ash, with organic parts below 1% unburnt organic content and boiler thermal efficiency of 86%. Low combustion temperature (850°C), application of a dry flue-gas cleaning method with lime and activated carbon and also fabric filters guarantee meeting strict emission requirements (Tab. 5) [20].

Table 5. Emission of harmful substances for the CFB boiler at the Lomellina LE1 incineration plant (dry exhaust, 11% volume O₂, average for 8h) [20]

| Compound | Average values [mg/Nm ³] | |
|-----------------|--------------------------------------|-------------|
| | Guaranteed value | Measurement |
| SO ₂ | 100 | 0.4 |
| NO _x | 200 | 152.2 |
| CO | 50 | 9.2 |
| Dust | 10 | 1.2 |

Municipal waste is, however, a small percentage of all waste in Poland, the rest is mining waste, of which 26% are wastes related to the extraction of hard coal. Almost 60 million tons of such waste in various forms (Fig. 7) is disposed of in various ways. The main direction their use are leveling and construction robots as well as aggregate production. About 30% this waste is used in domestic energy, partly in low-power heat-generating plants, but also in large combined heat and power plants equipped with fluidized bed furnaces [21].

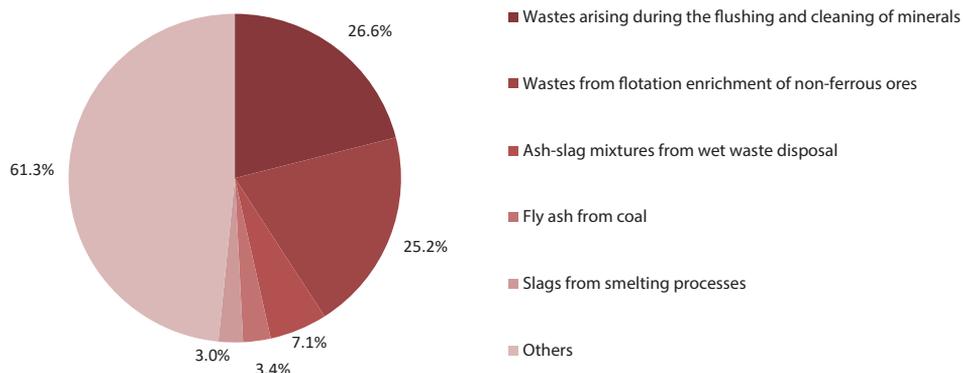


Fig. 7. Structure of mining waste generated in Poland in 2015 [21]

Coal sludge is used as a fuel for fluidized bed furnaces. Most often, however, it is used as a fuel additive. In this respect, it is important to highlight the great achievements of some of the national power plants with fluidized bed boilers. In most solutions, sludge is fed into the deposit in the form of silt-water pulp. Solutions are also known, mainly abroad, where sludge is the basic fuel for fluidized bed furnaces (Tab. 6) [20, 21].

Table 6. Selected coal-fired power plants and combined heat and power plants [20]

| Location | Type of fluidizing hearth | Power, MW _e | Carbon fuel | Emission guaranteed, mg/Nm ³ | | | |
|-----------------|---------------------------------|------------------------|-----------------------|---|-----------------|-----|------|
| | | | | SO ₂ | NO _x | CO | Dust |
| EC Katowice | CFB, cyclone cooled by steam | 120 | + sludge | 540 | 460 | 200 | 50 |
| El. Jaworzno II | CFB kompakt x 2 | 2x70 | + sludge | 560 | 470 | 310 | 50 |
| EC Siersza | CFB, hot cyclone | 2x336 | + sludge + biomass | 250 | 300 | 200 | 50 |
| El. Łagisza | CFB on supercritical parameters | 460 | + sludge + biomass | 200 | 200 | 200 | 30 |

4. Summary

Fluidized bed boilers have undergone significant metamorphosis since their invention. As time passed, new ways of using them began to be implemented. CFB technology now seems to dominate BFB technology and this will probably be continuous. Its important advantages are the ability to build high-power units and the use of low quality fuels. Technical environment for the combustion process allows emissions to be reduced at source, which is less expensive than flue gas cleaning in external installations.

CFB boilers are very widely used in combined heat and power plants, steel mills, or garbage incinerators. To a large extent, their success is based on the fact that they are environmentally friendly due to low emission of pollutants. It can therefore be expected that the use of these boilers will continue to grow because ecological matters are playing an increasingly important role in global politics.

References

- [1] Politechnika Wroclawska, <http://docplayer.pl/30344456-Dwie-podstawowe-konstrukcje-kotlow-z-cyrkulujacym-zlozem-cyklony-zewnetrzne-konstrukcja-compact.html> (access: 10.12.2017).
- [2] Basu P., *Circulating Fluidized Bed Boilers: Design, Operation and Maintenance*, Canada 2015.
- [3] Politechnika Wroclawska, <http://wme.pwr.edu.pl/>, http://webcache.googleusercontent.com/search?q=cache:PTTU6o7kjkJ:fluid.wme.pwr.wroc.pl/~spalanie/dydaktyka/spalanie_wyklad_energetyka/URZADZENIA/Spalanie_fluidalne.PDF+&cd=1&hl=pl&ct=clnk&gl=pl (access: 28.11.2017).
- [4] Engström F., *Fluidized bed boilers*, Finlandia 2017.
- [5] Eia, www.eia.gov/todayinenergy/detail.php?id=10151 (access: 27.02.2013).
- [6] Hanfei Z., Caixia L., Jun L., Wu Q., Yukun H., Changqing D., *Solid Waste Mixtures Combustion in a Circulating Fluidized Bed: Emission Properties of NO_x, Dioxin, and Heavy Metals*, Energy Procedia, Vol. 75, 2015, 987–992.
- [7] Trybuś T., *Fluidalne spalanie paliw jako metoda ograniczenia emisji dwutlenków siarki i tlenków azotu*, Wrocław 1995.
- [8] Energia, <https://energia.wortale.net/kotly-kotlownie,ac99/kociol-fluidalny,1597> (access: 10.12.2017).
- [9] Ekotechnologie, www.ekotechnologie.org/5-sf.html (access: 10.12.2017).
- [10] Jihui Ch., Xiaofeng L., *Progress of petroleum coke combusting in circulating fluidized bed boilers – A review and future perspectives*, Resources Conservation & Recycling, Vol. 49, 2006, 203–216. Thanet U., Suneerat F., *Co-firing of coal and rice straw pellet in a circulating-fluidized-bed reactor*, Energy Procedia, Vol. 138, 2017, 766–771.
- [11] Buhre B.J.P., Elliott L.K. C.D., Sheng Gupta R.P., Wall T.F., *Oxy-fuel combustion technology for coal-fired power generation*, Progress in Energy and Combustion Science, Vol. 31, 2005, 283–307.

- [12] Srivastava R.K., Miller C.A., C. Erickson & R. Jambhekar, *Emissions of Sulfur Trioxide from Coal-Fired Power Plants*, Journal of the Air & Waste Management Association, Vol. 127, 2014, 47–51.
- [13] Casagrande D.J., *Sulphur in peat and coal*, Geological Society, Special Publications, Vol. 32, 1987, 87–105.
- [14] Lunbo D., Haicheng S., Changsui Z., Wu Z., Xiaoping Ch., *Coal combustion characteristics on an oxy-fuel circulating fluidized bed combustor with warm flue gas recycle*, Fuel, Vol. 127, 2014, 47–51.
- [15] Neisler J., *Rozwój palenisk fluidalnych w energetyce*, Energetyka, Vol. 4, 2011, 33–36.
- [16] Jarema-Suchorowska S., Kurczak B., *Właściwości popiołów z kotłów fluidalnych w energetyce w aspekcie warunków gospodarczego wykorzystania tych odpadów*, Energetyka, Vol. 1, 2010, 39–43.
- [17] F-W, *Kotły z cyrkulacyjnym złożem fluidalnym na parametry nadkrytyczne*, FosterWheeler, 2011.
- [18] F-W, *Opis projektu Kotła fluidalnego na parametry nadkrytyczne dla Elektrowni Łagisza*, Foster Wheeler, 2011.
- [19] *Ochrona środowiska, Informacje i opracowania statystyczne Głównego Urzędu Statystycznego*, Warszawa 2016.
- [20] Hycnar J.J., *Paleniska fluidalne przykładem racjonalnego rozwiązywania problemów odpadów*, Polityka Energetyczna, Vol. 9, Zeszyt specjalny, 2006, 365–375.
- [21] Góralczyk S., Baic I., *Odpady z górnictwa węgla kamiennego i możliwości ich gospodarczego wykorzystania*, Polityka Energetyczna, Vol. 12, Iss. 2/2, 2009, 145–156.
- [22] Tomasz Cukiernik, <http://tomaszcukiernik.pl/artykuly/artykuly-wolnorynkowe/parametry-nadkrytyczne-w-technologie-fluidalnej> (access: 14.01.2018).

Dominika Misiura

Tomasz M. Majka (tomasz.majka@pk.edu.pl)

Department of Chemistry and Technology of Polymers, Cracow University of Technology

AN OVERVIEW ON OBTAINING FOAMED PET BY REACTIVE EXTRUSION

PRZEGLĄD SPOSOBÓW POZYSKIWANIA SPIENIONEGO PET METODĄ REAKTYWNEGO WYTŁACZANIA

Abstract

Many methods are used to obtain functional polymer foams. This review focuses on reactive extrusion of poly(ethylene terephthalate). This process is based on the reaction between PET and the appropriate blowing agent. The next step is the creation of foam by closing gas cells in the polymer matrix. This method of modification allows material with higher molecular weight to be obtained and, therefore, higher melt strength. The use of different chemical modifiers and their concentration influences properties of created foam. The enhanced features of foamed PET allow it to be used in many areas of application such as transport, construction or general industry. Another big advantage of this technique is the possibility of using recycled materials as the source of PET.

Keywords: PET; Foams; Reactive extrusion

Streszczenie

Do uzyskania funkcjonalnych pianek polimerowych stosuje się wiele metod. Niniejszy przegląd koncentruje się na reaktywnym wytłaczaniu poli(tereftalanu etyleny). Proces ten opiera się na reakcji pomiędzy PET i odpowiednim środkiem porotwórczym. Następnym krokiem jest wytworzenie piany przez zamknięcie komórek gazu w matrycy polimerowej. Ten sposób modyfikacji pozwala na uzyskanie materiału o wyższej masie cząsteczkowej. Zastosowanie różnych modyfikatorów chemicznych i ich koncentracja wpływa na właściwości otrzymanej piany. Udoskonalone właściwości spienionego PET pozwalają na stosowanie go w wielu obszarach, takich jak transport, budownictwo lub przemysł. Inną dużą zaletą tej techniki jest możliwość wykorzystania materiałów pochodzących z recyklingu jako źródła PET.

Słowa kluczowe: PET; Pianki; Reaktywne wytłaczanie

1. Introduction

Nowadays it's difficult to imagine living without synthetic organic polymers; the growing scale of their production is remarkable. Since the early 50's, plastic materials have managed to surpass other man-made materials. For many years, the largest area of application of polymer materials has been the packaging sector, accounting for 34.9% of the total demand for plastics. The packaging industry is dominated by bottles, films, bags and various types of containers made of polyethylene, polypropylene, polystyrene and polyethylene terephthalate (PET). Most monomers used in the production of these compounds are not biodegradable, thus most of these materials are accumulated in the environment. The large scale of production leads to many problems related to waste management; since 2015 almost 6300 Mt of plastic waste have been generated. Only 9 % of that has been recycled and over 79% has been accumulated. These amounts of misused products are pushing scientists towards looking for ways to reuse them. The disposal of polymeric waste is associated with the need to give the products obtained from such waste attractive features. On the basis of global trends, it can be concluded that mechanical recycling is the recommended way to reduce the share of waste accumulated in landfills [1].

The repeated processing of polymeric materials, however, is associated with the danger of their thermo-mechanical degradation and consequently with reduction of strength parameters. Improvements in properties can be obtained by mixing recycled materials with other polymers, although it's required to use the properly selected components. Another use of polymer waste is the production of porous materials, which in comparison to solid materials are less dense, and have better thermal insulation properties and greater vibration damping capacity. These features make the materials of cellular structure necessary for the construction, automotive and packaging industries. Factors limiting the development of porous materials are lower mechanical strength, complex processing and ecological considerations [2].

One of the polymers widely used in the production of bottles, containers, sheets, and fibres is poly(ethylene terephthalate). PET, as a thermoplastic polymer, is usually processed by extrusion or injection moulding; its thermal stability allows efficient and stable production of high-quality materials to be established. Another big advantage of PET processing technology is its recyclability. Due to the high annual consumption of products made of PET, it's important to find efficient ways of developing new products from waste materials. During the recycling processes, PET undergoes chemical, mechanical, and thermal degradation, which limits its use in many applications by lowering the molecular weight of the polymer and mechanical properties. Because of the low cost and low performance applications of the recycled material, at present, the widely accepted opinion is that the waste-PET mechanical recycling without a structural up gradation is not an efficient procedure [3].

This article presents an overview on the structural up-grading of PET by foaming it during reactive extrusion – a procedure considered efficient for the enhancement of its properties.

2. Reactive extrusion of PET

Reactive processing of poly(ethylene terephthalate) in order to extend macromolecular chains takes place in the same equipment as the melting process, at the polymer's melting point. This method bears both advantages of low costs and simple preparation. During this process a multifunctional compound reacts with PET nucleophilic end-groups to re-join polymer chains destroyed during its processing or use. Usually, by reactive processing, it is possible to obtain mechanical and rheological properties equal or higher than those of virgin polymers. That's why the reactive processing of PET is seen as a chance to add value to the post-consumption of polymers and to create products with added value. The reactively extruded material can be used without physical modification in main applications as bottles and foam sheets. The process of reactive extrusion is most commonly carried out at a temperature of 270–280 °C [2, 3].

2.1. Chain extenders

The chain extenders are mono-, di- or poly-functional organic compounds with low molecular weight ($M_n < 3000$). The typical extender functional groups are hydroxyl, carboxyl, anhydride, amine, epoxy, etc. Depending on its own chemical structure, each compound yields typical extension reactions [4].

2.1.1. Pyromellitic dianhydride

The modifying agents most often used are those belonging to the group of di-functional chain extenders, like bisepoxy compounds or diisocyanates. One of the widely used compounds is pyromellitic dianhydride (PMDA), which does not form by-products and leads to strongly cross-linked PET. PMDA is a tetra functional modifier that is thermally stable. It is efficient in proportion a of 0.2–0.3 % and raises the viscosity by depending on the reaction with PET hydroxide groups (Fig. 1) [5,7].

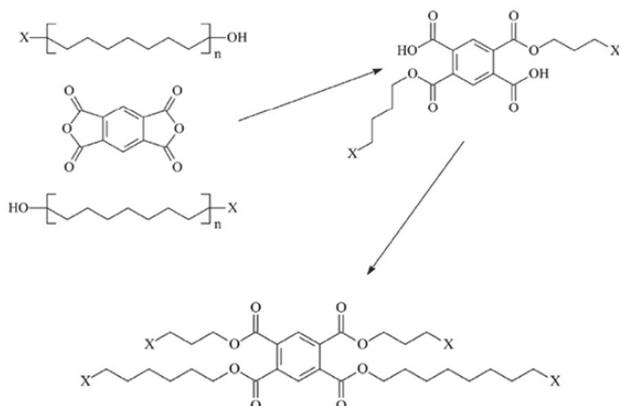


Fig. 1. PET chain extension with PMDA [5]

2.1.2. Epoxy compounds

Epoxy resins like tetraglycidyl diamino diphenyl methane (TDDM) (Fig. 2) esterify carboxyl groups and etherify hydroxyl groups at the end of the chain of PET macromolecules. In both reactions, secondary hydroxyls are formed that can react later with the carboxyl or epoxy groups (Fig. 3). This can cause the formation of branched structures. It is efficient in a proportion of 0.43% [5,8].

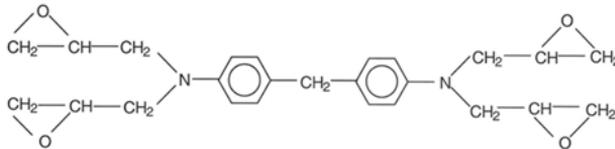


Fig. 2. Structure of tetraglycidyl diamino diphenyl methane [5]

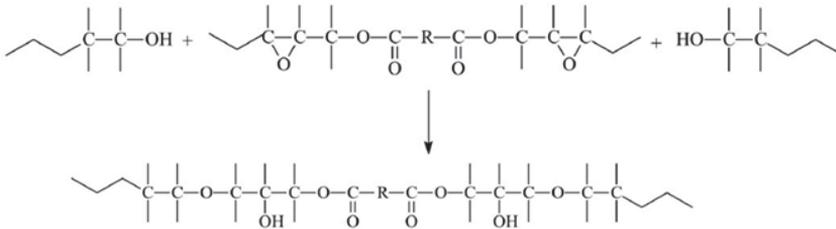


Fig. 3. PET chain extension with diepoxide [5]

3. Foaming process

The cellular structure can be produced in polymers by continuous or batch processes by means of solid, liquid or gaseous foaming agents. However, in any case the processes leading to the desired foaming capacities depend on the type of material used, the technology selected, and the parameters of processing. Their correct choice and precision are a challenge for many researchers [6].

In this process the following stages are distinguished:

- ▶ dissolving the gas in a polymer obtained under high pressure (solid polymer) or high temperature and pressure (polymer in the form of a liquid);
- ▶ nucleation of the gaseous phase germs in the system as a result of rapid change of the thermodynamic state of the material due to decompression and temperature change;
- ▶ the increase in the pore size and amount depends on the content of the foaming agent, the process parameters and the properties of the material;
- ▶ fixation of the structure by cooling to a temperature lower than the glass transition temperature of the polymer or its crosslinking [6, 7].

Depending on the type of polymer used, rigid or soft foams are obtained, and from the point of view of type, quantity and pore size, the porous materials are classified in terms of specific weight into foams of high ($> 240 \text{ kg/m}^3$), intermediate ($240\text{--}1.6 \text{ kg/m}^3$) and low ($<1.6 \text{ kg/m}^3$) density, and according to the type of pores, into closed or opened pores [6].

The selection of parameters of the foaming process is related to the type of ingredients used. A very important parameter is temperature, especially when chemical foaming agents are used; the temperature must be high enough to cause decomposition of the gaseous products necessary to produce the porous structure in the melted polymer, but it must not be too high to cause degradation of the plastic material. The most commonly used temperature for PET foaming is $270\text{--}280^\circ \text{C}$ [7].

PET as a foamed material possesses few limitation characteristics like unsatisfying viscosity that causes the collapsing of the foam structure during the stabilization phase of foam production. It's important to be aware of the need to increase polymer viscosity by the time of the end of foam rising. While keeping in mind the possibilities of increasing polymers molecular mass and viscosity by its reactive extrusion, it seems obvious to connect those two processes in order to obtain a high value material [8].

The agents most often used in PET foaming are chemical compounds like Hydrocerol CT534 or carbon dioxide used under high pressure [7].

The use of chemical foaming agents leads to the creation of the PET foam by decomposition of the agent. The gas produced from the blowing agent is dissolved in the polymer and then released to create separate phases. This method makes it possible to produce porous material with a cell size of $100\text{--}200 \mu\text{m}$ [8].

Using CO_2 as a PET foaming agent is popular because of its environmental friendly properties and high solubility in the polymer (when compared with other gases). Using a different pressure on the foamed material allows the concentration levels of the dissolved gas to be controlled and, therefore, the size of the pores created [8].

4. Conclusions

In the times when environmental safety is being more and more in danger, scientists are obliged to look for new ways of using waste materials. Recycling PET and turning it into a new, high value foam material has been the topic of interest of this article. As was described, the reactive extrusion of foamed PET leads to obtaining of a material characterized by better properties than the initial polymer. Even though it seems that the production of foamed PET has been completely studied, there's still plenty of room for improvements in this topic. The more the particular mechanisms of every step of production are examined, the more control over the final product will be obtained.

The main aim of this review is to show that the use of only two steps – chain extension and foaming, leads to the creation of a highly useful product with possibilities of use in many branches of industry, like construction, automotive, and packaging.



References

- [1] Geyer, Jambeck, *Production, use, and fate of all plastics ever made*, Law Sci. Adv. 2017, 3.
- [2] Raffa, Coltelli, Savi, Bianchi, Castelvetro, *Chain extension and branching of poly(ethylene terephthalate) (PET) with di- and multifunctional epoxy or isocyanate additives: An experimental and modelling study*, Reactive & Functional Polymers, 2012, 72.
- [3] Tavares, Silva, Lima, Andrade, Canedo, *Chain extension of virgin and recycled polyethylene terephthalate*, Polymer Testing, 2016, 50.
- [4] Awaja, Daver, Kosior, Cser, *The Effect Of Chain Extension On The Thermal Behaviour And Crystallinity Of Reactive Extruded Recycled Pet*, Journal of Thermal Analysis and Calorimetry, 2004, 78.
- [5] Dimonie, Socoteanu, Pop, Fierascu, Fierascu, Petrea, Zaharia, Petrache, *Material Recycling – Trends and Perspectives: Overview on Mechanical Recycling by Chain Extension of POSTC-PET Bottles*, InTech, 2012.
- [6] Kozłowski, Kozłowska, Frąckowiak, *Materiały polimerowe o strukturze komórkowej*, Polimery, 2010, 55.
- [7] Maio, Coccorullo, Montesano, Incarnato, *Chain Extension and Foaming of Recycled PET in Extrusion Equipment*, Macromol. Symp., 2005, 228.
- [8] Japon, Leterrier, Manson, *Recycling of Poly(Ethylene Terephthalate) Into Closed-Cell Foams*, Polymer Engineering and Science, 2000, 40.

Volodymyr Samotyy (vsamotyy@pk.edu.pl)

Department of Automatic Control and Information Technology, Cracow University
of Technology

Ulyana Dzelendzyak

Andriy Pavelchak

Department of Computer System and Automatic, Lviv Polytechnic National University,
Ukraine

AN EVOLUTIONARY MODEL FOR THE PARAMETRIC OPTIMISATION OF
ELECTROMAGNETIC INSTRUMENTS OF VARIABLE STRUCTURES

MODEL EWOLUCYJNY OPTIMALIZACJI PARAMETRYCZNEJ URZĄDZEŃ
ELEKTROMAGNETYCZNYCH O ZMIENNEJ STRUKTURZE

Abstract

This paper discusses the principle of constructing an evolutionary model for the parametric optimisation of electromagnetic instruments with solid-state valves. To illustrate the method, a triple voltage scheme was selected – this converts variable voltage into constant voltage and at the same time, triples the amplitude. Valve operation was modelled according to the ideal key diagram; the considered resistance was that of an open valve.

Keywords: evolutionary model, parametric optimisation, ideal key, voltage tripler, fixed mode, additional logic variables

Streszczenie

W pracy rozpatrzono zasady tworzenia modelu ewolucyjnego optymalizacji parametrycznej urządzeń elektromagnetycznych zawierających zawory półprzewodnikowe. Do ilustrowania metody wybraliśmy schemat przetwornicy napięcia zmiennego na stałe o potrójnej amplitudzie. Wykonuje on przetwarzanie napięcia zmiennego na stałe o trzykrotnej amplitudzie. Model diody wybieramy w postaci zawora idealnego. Przy czym jest uwzględniony jego opór w trybie otwartym.

Słowa kluczowe: model ewolucyjny, optymalizacja parametryczna, zawór idealny, przetwornica napięcia zmiennego na stałe o potrójnej amplitudzie, przebiegi ustalone, dodatkowe zmienne logiczne

1. Introduction

The conversion of voltage signal parameters is one of the most common forms of conversion in power electronics. This includes, inter alia, constant-to-variable, variable-to-constant, constant-to-constant and variable-to-variable voltage conversion. Another type of conversion worth mentioning is the change of output voltage amplitude with its galvanic distinction between input and output signals. Such converters are used in power supply units as modulators and also for the frequency control of electric motors. The devices which convert the constant voltage to variable voltage are called inverters, alternating current to direct current - rectifiers, direct current to direct current - converters, alternating current to alternating current - frequency converters.

The change of output voltage amplitude is performed by, for example, systems of rectifiers with multiplication of voltage (twofold, threefold, etc.). It should be noted that the base elements in the specified converters are variable-to-constant voltage converters and constant-to-variable voltage converters, i.e. rectifiers and inverters. Converters can be obtained directly by the linear connection of two converters, an inverter and a rectifier, whereas in frequency converters, their position should be switched – a rectifier should be placed on the input and an inverter on the output.

The use of mathematical modelling methods provides for development of mathematical models of voltage transducers. The bases of most mathematical models are the equations of the dynamics of the examined device. The compatibility of this solution to actual physical processes depending on how these equations correspond to the physics of the processes that take place in the voltage transducer.

Having written down the dynamics equation and the initial conditions of the state variables, the result is the Cauchy problem. Numerical methods of integration are used to solve the system of nonlinear differential equations because the task does not have an analytical solution. Integrating dynamics equations in a certain interval a transitional process settlement. If integration is performed with a fairly significant interval, it is possible to receive a fixed mode; however, it is never known in advance what that interval should be. So it is purposeful here to apply methods which have clear condition in entering the stationary mode. Such a condition is the persistence equation.

Analysis of transducers fixed work modes is a harder task than the settlement of transitional processes because it additionally requires the calculation of initial processes which meet the requirement for periodicity. The tested voltage transducers include both controlled and uncontrolled solid-state valves. Their volt-ampere properties feature high tortuosity when the valve crosses zero, which considerably hinders the modelling of their work modes. Two essentially different solid-state valve models exist. The first is based on the electric wheel theory with concentrated parameters, and the other model applies the magnetic field theory methods. The first model is divided into two further models; the first replaces the valve with the *RLC* link with variable parameters, and the other models it according to the ideal key diagram. In the first model, when the valve is open, the value of the active *R* link resistance is insignificant. When the voltage on the valve is negative, the received *R* resistance is quite high (hundreds of MOm). A risk of high overload is potentially present when comparably low valve

current is multiplied by its high resistance. To avoid this, the valve current crossing through zero must be determined. This considerably hinders the construction of the algorithm for numerical integration of dynamic equations.

The ideal key model leads to the appearance of a variable electric field structure – this means that the number of circuits and electric nodes changes depending on commutation. This has a direct effect on the voltage transducer dynamics equations. Every combination of open and closed valves is described with an algebraic-differential equations system. Such a situation is rather awkward because it requires going through different procedures depending on the execution of the conditions of valve opening and closing. It is proposed to introduce additional logical variables into dynamics equations which gain a value of 0, ± 1 . This allows the conversion of the entire system of equations into a single equation. These logical variables are components of the matrix elements of the dynamics equation coefficients and their values vary depending upon the conditions of the valve opening and closing.

Therefore, when constructing mathematical models of control system voltage transducers, one has to stick to the valve model according to the ideal key diagram using additional logical variables. This allows the description of the voltage transducers in the differential equations modes. It must be noted that voltage transducers are widely used in automatics and control systems, observation systems, navigational systems, and in radio-electronics, etc. The existence of controlled and uncontrolled solid state valves in them makes it an extremely non-linear task; therefore, the issues solved in this paper are current and significant both in practical and theoretical terms.

2. Analysis of publications

A significant number of scientific works have been dedicated to voltage parameter transducers using solid state keys. A few of, were published in the last several years, will be considered below. A variable voltage regulator was examined in one of these pieces of work [1]. An attempt was made to approximate the form of the output signal to the sinusoid. The work of solid state keys was modelled by a changeover matrix – this means that non-linear valve features were not considered in the work. Whereas in [2], a single-phase current phase corrector was examined. A controller and PI regulator were used to control the device. A switching function was also used here for the modelling of valve diagrams. No analysis of parametric optimisation of the control process exists.

In work [3], width-impulse modulation was used to control the single-phase corrector. Realised transducer mathematical model acquired with the switching function. The control system was also examined in the violation of exploitation rules conditions. In work [4], a new triple-phased topology of an active rectifier was proposed. Such a topology lowers power losses in comparison to known diagrams of voltage rectification. Experimental studies were conducted in different exploitation conditions.

Very often, the thyristor voltage transducers lead to non-linear distortion in power supply networks. To eliminate such a phenomenon, the use of a configuration with many bridge

impulse transducers was proposed [5]. These are built using a transformer with multiple windings. Switching transistors often causes an overload that leads to them becoming damaged. In work [6], mild transistor switching was proposed – this eliminates the risk of an overload of the capacitor discharge by the transistor.

In work [7], power supply sources for illumination devices were examined – these are classic alternating-to-direct voltage impulse transducers (ac-dc). An asymmetric half-bridge was used here (AHB). The proposed methodology of applying AHB increases its effectiveness by as much as 94.5%. Model Predictive Control (MPC) [8] in thyristor voltage transducers is also known. Here, this was used for the two-level triple-phase transducer and compared with an array with similar approaches. In the examined examples of modelling the work of voltage transducers, open valve resistance is not considered. It is a non-linear valve current function. Furthermore, no analysis of the parametric optimisation of the work of voltage transducers exists. Our paper is dedicated to solving such tasks.

3. The dynamics equation of the voltage tripler

To illustrate the task, we will consider an alternating-to-direct voltage transducer with simultaneous amplitude tripling. It should be noted here that processing for such a type is possible if the load has high resistance (several kOm).

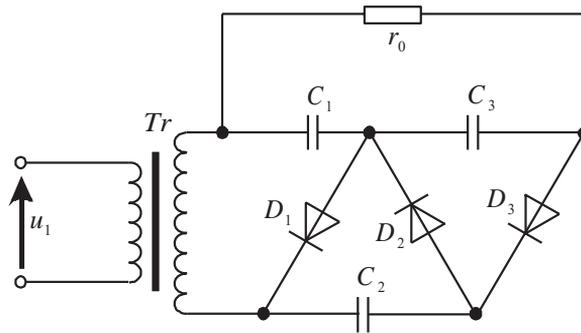


Fig. 1. Basic diagram of voltage tripler

A basic diagram of such voltage tripler is presented in Fig. 1. This includes a transformer (Tr), three diodes (D_1, D_2, D_3), three condensers (C_1, C_2, C_3) and load (r_0). In the positive wave, the condenser C_1 is loaded to the amplitude of the output voltage of the transformer. In the negative wave, the condenser C_2 is loaded up to double the condenser voltage C_1 . This cycle is ended with the condenser charging up to C_3 double the condenser voltage C_1 . When voltage is added on condensers C_1 and C_3 , the result is triple voltage on the load r_0 .

When formulating the dynamics equations, the parameters of the primary side of the transformer must be considered led to the secondary side, due to the number of coils, and the operation of solid state valves will be presented according to the ideal key diagram. The notion of ‘ideal’ will be understood as a key in which resistance in the closed condition is limitless and in the

open condition, it is constant, e.g. equal to zero. The idea of construction of mathematical models of such instruments consists of such an algorithm. First, it is necessary to explain the possible number of combinations of open and closed valves – for each of these, their own algebraic-differential equation system must be provided. Their common features must be determined and, using additional logical variables, a single general system of equations must be formulated.

This allows the obtaining of four possible combinations of open and closed valves in the given diagram: 1) D_1 – open, D_2, D_3 – closed; 2) D_2 – open, D_1, D_3 – closed; 3) D_3 – open, D_1, D_2 – closed; 4) D_1, D_2, D_3 – closed.

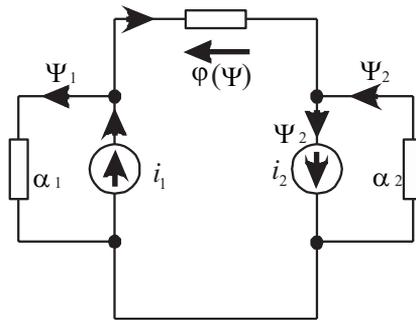


Fig. 2. Calculation of transformer magnetic field

Let us consider the dynamics equations for the first combination of the valve condition. In order to formulate these, we need the diagrams of change of the electric and magnetic field of the tripler. Calculation of the magnetic field is presented in Fig. 2 and for the electric winding circuits – Fig. 3. The proper equations for the calculation of the magnetic field (Fig. 2) are as follows:

$$\Psi_1 = \psi_1 + \psi, \quad \Psi_2 = \psi_2 + \psi, \quad (1)$$

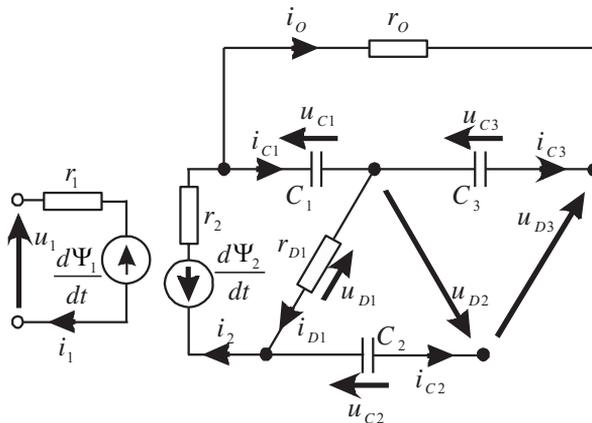


Fig. 3. Calculation of transformer electrical circuits

where ψ_1, ψ_2 – coupled coil dispersion streams; ψ – main steam coupling. Both here and further in this paper, the indices ‘1’ and ‘2’ indicate a connection with the primary and secondary winding of the transformer.

For dispersion systems (Fig. 2) the resulting equation is

$$i_1 = \psi_1 \alpha_1, \quad i_2 = \psi_2 \alpha_2, \quad (2)$$

where $\alpha_1, \alpha_2, i_1, i_2$ – values replaced with inductivity of dispersion and current of the winding.

Let us substitute (2) with (1) and determine the transformer winding current

$$i_1 = \alpha_1 (\Psi_1 - \psi), \quad i_2 = \alpha_2 (\Psi_2 - \psi). \quad (3)$$

According to the second Kirchhoff’s law, for the magnetic field (Fig. 2), the equation is

$$i_1 + i_2 = \phi(\psi), \quad (4)$$

where $\phi(\psi)$ – transformer core magnetising curve.

The transformer winding equations according to the calculation in Fig. 3 are as follows:

$$\frac{d\Psi_1}{dt} = u_1 - r_1 i_1, \quad \frac{d\Psi_2}{dt} = -u_{C1} - r_2 i_2 - u_{D1}, \quad (5)$$

where Ψ_1, Ψ_2, r_1, r_2 – full coupling of streams and resistance of transformer winding; u_1, u_{C1} – power supply and condenser voltage C_1 .

Calculating the time derivative from equations (3) and (4) will give the result regarding the time derivative of the basic coupling

$$\frac{d\psi}{dt} = g_1 \frac{d\Psi_1}{dt} + g_2 \frac{d\Psi_2}{dt}, \quad g_1 = \frac{\alpha_1}{\alpha^* + \alpha_1 + \alpha_2}, \quad g_2 = \frac{\alpha_2}{\alpha^* + \alpha_1 + \alpha_2}. \quad (6)$$

Let us calculate the time derivative of the second equation (3) and enter (6) in the obtained equation result

$$\frac{di_2}{dt} = a_{21} \frac{d\Psi_1}{dt} + a_{22} \frac{d\Psi_2}{dt}, \quad a_{21} = -\alpha_2 g_1, \quad a_{22} = \alpha_2 (1 - g_2). \quad (7)$$

The primary winding current must be determined analytically, according to (4)

$$i_1 = \phi(\psi) - i_2. \quad (8)$$

The obtained equations must be supplemented with condenser equations

$$\frac{du_{C1}}{dt} = \left(i_2 - \frac{u_{C1} + u_{C3}}{r_0} \right) / C_1, \quad \frac{du_{C2}}{dt} = 0, \quad \frac{du_{C3}}{dt} = -\frac{u_{C1} + u_{C3}}{r_0 C_3} \quad (9)$$

where r_0 – load resistance.

The load current must be calculated according to the following formula:

$$i_o = (u_{c1} + u_{c3}) / r_o . \quad (10)$$

Valve D_1 closed under condition

$$i_{D1} = i_2 \leq 0 . \quad (11)$$

Let us consider the dynamics equations for the second combination of the valve condition. The calculation of the winding electrical circuits is presented in Fig. 4. The transformer equation remains unchanged, except for the second equation (5)

$$\frac{d\Psi_2}{dt} = -u_{c1} - r_2 i_2 + u_{c2} + u_{D2} \quad (12)$$

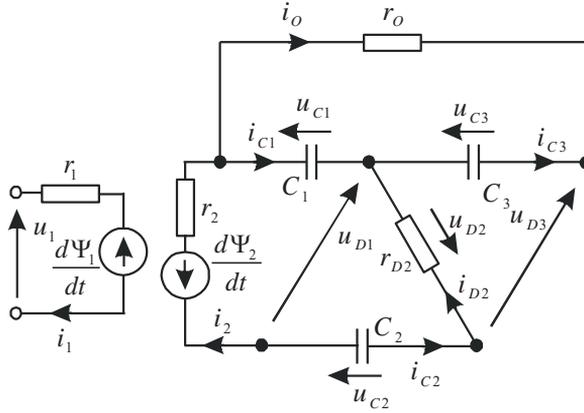


Fig. 4. Calculation of transformer electrical circuits

The condenser equations will assume the following form:

$$\frac{du_{c1}}{dt} = \left(i_2 - \frac{u_{c1} + u_{c3}}{r_o} \right) / C_1, \quad \frac{du_{c2}}{dt} = -i_2 / C_2, \quad \frac{du_{c3}}{dt} = -\frac{u_{c1} + u_{c3}}{r_o C_3} \quad (13)$$

Valve D_2 closed under condition

$$i_{D2} = -i_2 \leq 0, \rightarrow i_2 \geq 0 . \quad (14)$$

Now, let us consider the dynamics equations of the third valve combination condition. Calculation of the electrical circuits is presented in Fig. 5. The transformer equations remain unchanged, except for the second equation (5)

$$\frac{d\Psi_2}{dt} = -u_{c1} - r_2 i_2 + u_{c2} - u_{c3} - u_{D3} \quad (15)$$

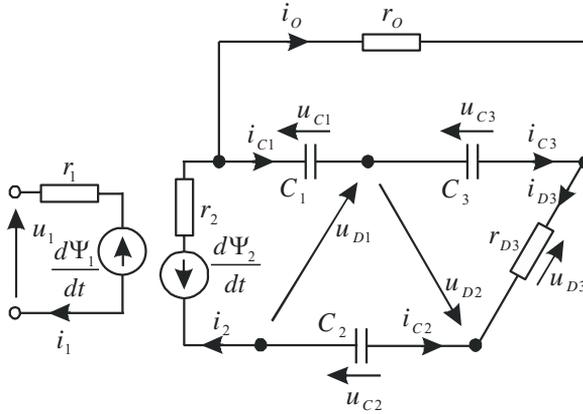


Fig. 5. Calculation of transformer electrical circuits

The condenser equations assume the following form:

$$\frac{du_{C1}}{dt} = \left(i_2 - \frac{u_{C1} + u_{C3}}{r_o} \right) / C_1, \quad \frac{du_{C2}}{dt} = -i_2 / C_2, \quad \frac{du_{C3}}{dt} = \left(i_2 - \frac{u_{C1} + u_{C3}}{r_o} \right) / C_3. \quad (16)$$

Valve D_3 is closed under condition

$$i_{D3} = i_2 \leq 0. \quad (17)$$

Let us consider the dynamics equations for the fourth combination of the valve condition. The calculation of winding electrical circuits is presented in Fig. 6. When all valves are closed, the transformer is disconnected from load ($i_2=0$). For this reason, equations change, namely:

$$\frac{d\psi}{dt} = g_1 \frac{d\Psi_1}{dt}, \quad g_1 = \frac{\alpha_1}{\alpha' + \alpha_1}. \quad (18)$$

$$\frac{d\Psi_2}{dt} = \frac{d\psi}{dt}. \quad (19)$$

$$\frac{di_2}{dt} = 0. \quad (20)$$

The capacitor equations will take the following form:

$$\frac{du_{C1}}{dt} = -\frac{u_{C1} + u_{C3}}{r_o C_1}, \quad \frac{du_{C2}}{dt} = 0, \quad \frac{du_{C3}}{dt} = -\frac{u_{C1} + u_{C3}}{r_o C_3}. \quad (21)$$

These equations must be filled in with conditions for opening valves

$$u_{D1} = -u_{C1} - \frac{d\psi}{dt} > u_{open} = 0, \quad (22)$$

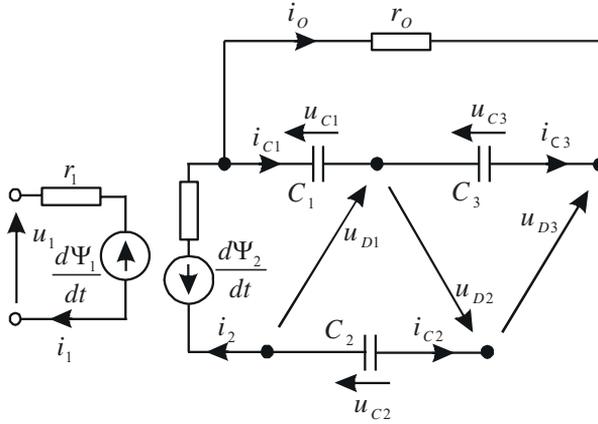


Fig. 6. Calculation of transformer electrical circuits

$$u_{D2} = u_{C1} - u_{C2} + \frac{d\Psi}{dt} > u_{open} = 0, \quad (23)$$

$$u_{D3} = -u_{C1} + u_{C2} - u_{C3} - \frac{d\Psi}{dt} > u_{open} = 0, \quad (24)$$

Let us introduce additional logical variables k_1, k_2, k_3 which take value 0 when the valve is closed and value 1 when it is open. When, upon fulfilment of condition (22), the variable k_1 takes value 1, upon fulfilment of condition (23) $k_2=1$, upon fulfilment of condition (24) $k_3=1$. Whereas, upon fulfilment of condition (11) $k_1=0$, upon fulfilment of condition (14) $k_2=0$, upon fulfilment of condition (17) $k_3=0$.

The result of the above is four different equation systems for each combination of valve status. Upon comparison and application of the additional logical variable, it is possible to narrow it down to the following system:

$$\frac{d\Psi}{dt} = g_1 \frac{d\Psi_1}{dt} + g_2 \frac{d\Psi_2}{dt}, \quad g_1 = \frac{\alpha_1}{\alpha'' + \alpha_1 + k\alpha_2}, \quad g_2 = \frac{k\alpha_2}{\alpha'' + \alpha_1 + k\alpha_2}, \quad (25)$$

$$\frac{di_2}{dt} = a_{21} \frac{d\Psi_1}{dt} + a_{22} \frac{d\Psi_2}{dt}, \quad a_{21} = -k\alpha_2 g_1, \quad a_{22} = k\alpha_2 (1 - g_2), \quad (26)$$

$$\frac{du_{C1}}{dt} = \left(k_1 i_2 - \frac{u_{C1} + u_{C3}}{r_0} \right) / C_1, \quad (27)$$

$$\frac{du_{C2}}{dt} = -(k_2 + k_3) i_2 / C_2, \quad (28)$$

$$\frac{du_{C3}}{dt} = \left(k_3 i_2 - \frac{u_{C1} + u_{C3}}{r_0} \right) / C_3, \quad (29)$$

$$\frac{d\Psi_1}{dt} = u_1 - r_1 i_1, \quad \frac{d\Psi_2}{dt} = -u_{c1} + (1 - k_1)u_{c2} - k_3 u_{c3} - r_2 i_2 + u_D, \quad (30)$$

where $k = k_1 + k_2 + k_3$, $u_D = -k_1 u_{D1} + k_2 u_{D2} - k_3 u_{D3}$.

4. Results of the voltage tripler modelling

A program in C# language was prepared for the mathematical modelling of the device and simulation of its dynamic processes was performed.

One-phase voltage of the transformer power supply was set with the formula

$$u_1 = U_m \sin(2\pi ft), \quad (31)$$

where $U_m = 311 \text{ V}$, $f = 50 \text{ Hz}$.

The calculations of the mathematical model were conducted with the following device parameters values: $r_1 = r_2 = 0.1 \Omega$; $r_o = 9000 \Omega$; $\alpha_1 = 100 \text{ H}^{-1}$; $\alpha_2 = 200 \text{ H}^{-1}$; $C_1 = 40 \mu\text{F}$; $C_2 = 600 \mu\text{F}$; $C_3 = 400 \mu\text{F}$. The magnetisation curve is approximated by formula (32).

$$\phi(\psi) = \begin{cases} m_1 \psi & \text{if } |\psi| > \psi_1 \\ S_3(\psi) & \text{if } \psi_1 \leq |\psi| \leq \psi_2 \\ m_2 \psi - m_0 & \text{if } |\psi| > \psi_2 \end{cases} \quad (32)$$

where $m_1 = 0.25 \text{ H}^{-1}$; $m_2 = 3 \text{ H}^{-1}$; $a_0 = 1.8 \text{ A}$; $\psi_1 = 0.2 \text{ Wb}$; $\psi_2 = 0.9 \text{ Wb}$; $\varphi(\psi_1) = 0.05 \text{ A}$; $\varphi(\psi_2) = 0.09 \text{ A}$; $S_3(\psi)$ – cubic spline.

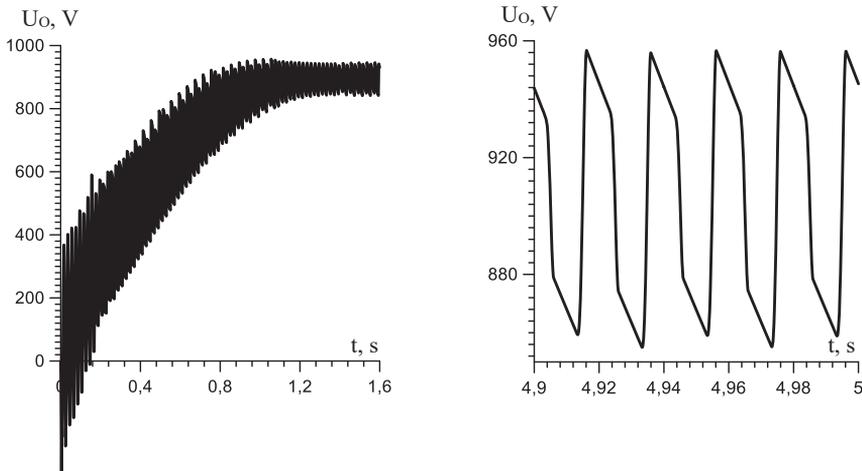


Fig. 7. Transient response of the voltage tripler

Fig. 7 presents the results of simulation of our voltage tripler. The device really triples our input voltage; however, with selected capacitor parameters, very high pulsations of input voltage in the range of 105 V are observed. In order to improve the output specification of the device, it is necessary to perform the optimisation for capacitor parameters.

Table 1 shows the values of volt-ampere specification for diode S1M.

Table 1. Table 1. The voltage-ampere specification of diode S1M at 25 °C

| I_p, A | U_p, V | R_d, Ω |
|----------|----------|---------------|
| 0.01 | 0.67 | 67 |
| 0.1 | 0.78 | 7.8 |
| 1 | 0.97 | 0.97 |
| 10 | 1.41 | 0.141 |

The other issue we were interested in was the impact of non-linear diode resistances on the mathematical model. In our model of the device, the applied model was the model of ideal key for diodes. For this reason, an additional test concerning the impact of the diode model on the final results was performed.

The function of dependency of resistance on the current of diode S1M was approximated with the formula

$$R_D(i_D) = \begin{cases} R_{D_{\max}} & \text{if } |i_D| \leq I_{D_{\min}} \\ 1.0393 \cdot i_D^{-0.8936} & \text{if } I_{D_{\min}} < |i_D| < I_{D_{\max}} \\ R_{D_{\min}} & \text{if } |i_D| \geq I_{D_{\max}} \end{cases} \quad (33)$$

where $R_{D_{\max}} = 67 \Omega$; $R_{D_{\min}} = 0.141 \Omega$; $I_{D_{\max}} = 10 A$; $I_{D_{\min}} = 0.01 A$.

The mathematical model was considered the threshold of the voltage of opening diodes which is applied in formulas (22–24) with determination $u_{open} = 0.67 V$. In the equations of resistance dynamics, diodes R_D are systematically switched off with resistance r_2 and $i_D = i_2$. In the case of the modelling performed with consideration to the diode model, the qualitative specification of the device did not change – numeral changes in the output signal in the set mode were present in the five-digit series (maximum and minimum amplitude was registered).

5. Results of the voltage tripler optimisation

The selection of the parameter values of the voltage tripler was performed with the use of a classical genetic algorithm with the representation of genes with real digits [10, 11]. At performance, certain capability assumed for the genetic algorithm: to suspend/renew algorithm operation, possibility to change algorithm settings in the suspension mode (selection of

numeral population, number of generations, selection of method of pairing, selection, crossing, mutation, change of likelihood of gene mutation, elitism settings); it was foreseen that there could be a possibility to maintain transitional data of the search for optimum solution with parameters set for the genetic algorithm and continue the search from the maintained point.

The device parameters should be harmonised in the range [0, 1] for the genetic algorithm. Coding the parameters of the tested device with genes and reverse decoding is performed according to formulas (34)

$$gene_i = \frac{param_i - valueMin_i}{valueMax_i - valueMin_i} \quad (34)$$

$$param_i = valueMin_i + gene_i \cdot (valueMax_i - valueMin_i)$$

In our performance of the genetic algorithm, the initial population is generated in a random manner in harmonised ranges [0, 1]. The selection of individuals in a population is performed with linear ranking

$$Fitne\beta(Pos) = 2 - SP + 2 \cdot (SP - 1) \cdot \frac{Pos - 1}{Nind - 1} \quad (35)$$

where Pos – position of individuals in the population (the least adapted individuals have $Pos = 1$; the best adapted have $Pos = Nind$), $Nind$ – quantity of individuals in the population, SP – co-efficient of selection impact can be significant in the range [1.0; 2.0]. According to value $Fitne\beta$, the quantity of individual entries in the population is determined.

While pairing individuals, two operators were applied: «better with better» and «better with worse». At the beginning, we used operator «better with better» and at the end of the search for the optimum solution at the introduction of the population, we used operator «better with worse».

For crossing, the operator which imitates one-point binary crossing [11] was used. For mutation, operator Uniform was used.

The performance of the genetic algorithm was performed in C# language. An in-built generator of pseudo-random numbers with the principle of even distribution was used to generate random values which were built on the basis of the subtraction algorithm of random numbers developed by D. Knuth. The calculations of fitness value (adaptation function) for individuals separate depending on the existence of quantity of physical (logical) cores of the PC processor.

For the optimisation of the dynamic specification of the voltage tripler, the aforementioned genetic algorithm was applied.

The condenser values not only have an effect on the pulse size of the output signal, they also change its periodicity. Therefore, the method for accelerated switching into the fixed mode was not used, and for the purpose of search for the optimum solution, the end section of the transitional process was used.

Integrating current dynamics equations was performed in the time interval of $T = 5$ seconds. As a criterion for the fitness function value, we selected the impulse value of the output voltage at $0.9 \cdot T$. This means that the fitness values were calculated according to the following formula:

$$\begin{aligned} \text{Fitness} &= U_{O_{\max}} - U_{O_{\min}} \\ \text{if } (U_{O_{\min}} < 850) \text{ then: } \text{Fitness} &= \text{Fitness} + 850 - U_{O_{\min}} \end{aligned} \quad (36)$$

When calculating the fitness value (36), an additional condition was introduced that ensures the rejection of parameters at which an output signal lower than 850 V is generated.

Fig. 8 presents the result of the sought optimum solution for the dynamic characteristics of the instrument, according to the criterion set for the fitness function with such determined limits of the condenser values: $C_1 = [10^{-5}, 0.005]$ F; $C_2, C_3 = [10^{-7}, 0.005]$ F.

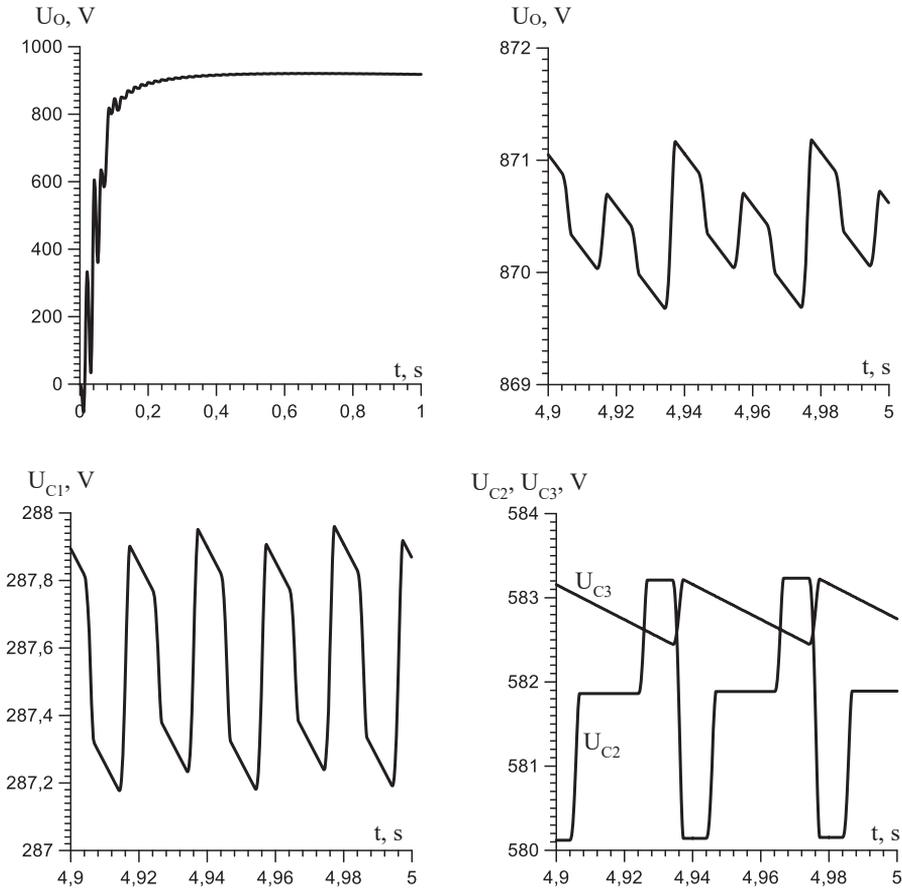


Fig. 8. Transient response of the voltage tripler with $R_0 = 9000 \Omega$, $C_1 = 4.986 \text{ mF}$, $C_2 = 1.266 \text{ mF}$, $C_3 = 4.654 \text{ mF}$

The following settings were selected for the genetic algorithm: the population count was selected with chromosome 40 or 50; the probability of mutation was selected within the range of 5 to 15%; selective pressure coefficient was 1.7 or 1.8; chromosome 1 was selected for the elitism. The obtained characteristics in the fixed mode have quite a low pulse at a level of 1.57 V and a short time for returning to the operating mode. The only downside is the high value of the condenser capacity.

Fig. 9 presents the result of the search for the optimum value in the scale of condenser values $C_1, C_2, C_3 = [10^{-7}, 0.0005]$ F. This means that at the beginning, the condenser capacity value was limited (restricted). Respectively, the dynamic characteristics of the instrument feature a smoother switch into the fixed mode and the pulse value in the fixed mode reaches 10.8 V.

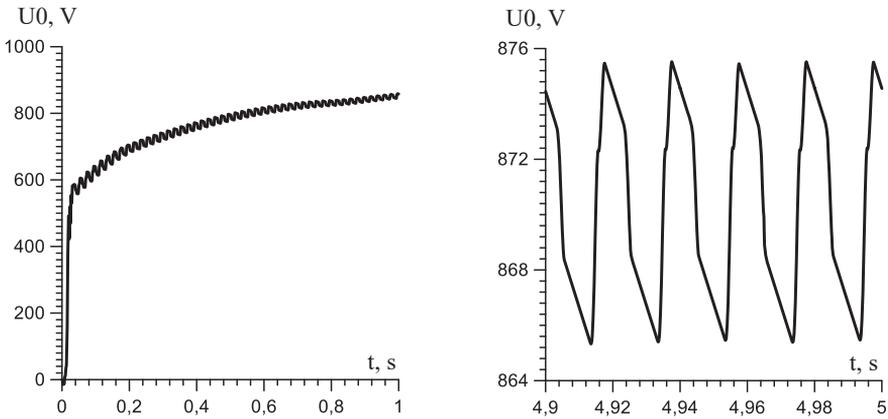


Fig. 9. Transient response of the voltage tripler with $R_o = 9000 \Omega$, $C_1 = 498.1 \mu\text{F}$, $C_2 = 24.42 \mu\text{F}$, $C_3 = 498.9 \mu\text{F}$

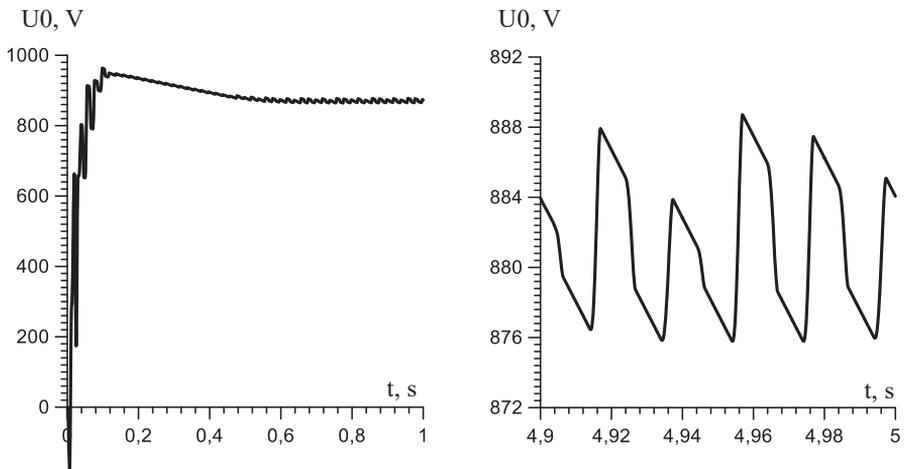


Fig. 10. Transient response of the voltage tripler with $R_o = 5000 \Omega$, $C_1 = 499.9 \mu\text{F}$, $C_2 = 252.9 \mu\text{F}$, $C_3 = 494.4 \mu\text{F}$

It would also be interesting to investigate the operation of the instrument at a lower load resistance set at $5 \text{ k}\Omega$ (Fig. 10). The search for the optimum performance was performed at a condenser value scale of $C_1, C_2, C_3 = [10^{-6}, 0.0005] \text{ F}$. The pulse value in the fixed mode was at a level of 13.6 V . In the case of lower values of the instrument load resistance, it was impossible to reach the strip value of 850 V .

6. Conclusion

Using the proposed mathematical model of the constant-to-variable voltage transducer with concurrent tripling of the amplitude, parameter optimisation of the instrument was performed. The condenser capacity values were selected by applying the classical genetic algorithm with the representation of genes by real digits. The conducted optimisation allowed the obtaining of good quality dynamic parameters of the instrument. The prepared mathematical model of the voltage tripler is universal and simple for algorithm setting.

References

- [1] Choi Jae-Ho, Ji Jun-Keon, Park Min-Ho, *A novel voltage-regulated current controlled PWM-VSC converter with unity power factor*, Proceedings 14 Annual Conference of Industrial Electronics Society, Singapore, 24–28 October, 1988, 587–592.
- [2] Kanaan H.Y., Al-Haddad K., Hayek A., Mougharbel I., *Design, study, modelling and control of a new single-phase high power factor rectifier based on the single-ended primary inductance converter and the Sheppard-Taylor topology*, IET Power Electronics, Vol. 2, Issue 2, 2009, 163–177.
- [3] Kanaan H.Y., Al-Haddad K., Fadel M., *Modeling and control of a two-switch asymmetrical half-bridge Boost Power Factor Corrector for single-phase rectifiers*, IEEE 22nd International Symposium on Industrial Electronics, Taipei, Taiwan, 28–31 May, 2013, 1–6.
- [4] Li Y., Junyent-Ferre A., Rodriguez-Bernuz J-M., *A Three-Phase Active Rectifier Topology for Bipolar DC Distribution*, IEEE Transactions on Power Electronics, V. PP, Issue 99, 2017, 1–1.
- [5] Drozdowski P., Jeleń M., *Metoda eliminacji harmonicznego prądu przekształtnika sieciowego napędu trakcyjnego*, Technical Transactions, 1-E/2011, 53–65.
- [6] Mazgaj W., Rozegnał B., Szular Z., *A novel soft switching system for three-phase voltage source inverter*, Technical Transactions, 2-E/2016, 3–15.
- [7] Arias M., Fernández M., González D., Sebastián J., Balocco D., Diallo A., *Improving the design of the asymmetrical half-bridge converter without electrolytic capacitor for low-output-voltage ac-dc LED drivers*, IEEE Energy Conversion Congress and Exposition, NC, USA, 15–20 September, 2012, 3241–3248.
- [8] Tarisciotti L., Zanchetta P., Watson A., Clare J.C., Degano M., Bifaretti S., *Modulated Model Predictive Control for a Three-Phase Active Rectifier*, IEEE Transactions on Industry Applications, Vol. 51, Issue 2, 2015, 1610–1620.

- [9] Samotyy V., *Evolutionary optimization of DC motor control system*, Technical Transactions, 3-E/2016, 215–227.
- [10] Sivanandam S.N., Deepa S.N., *Introduction to Genetic Algorithms*, Springer-Verlag Berlin Heidelberg, 2008.
- [11] Randy L. Haupt, Sue Ellen Haupt, *Practical genetic algorithms*, 2nd ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 2004.

Leonid Moroz

Department of Security of Information Technology, Lviv Polytechnic National University, Ukraine

Volodymyr Samotyy (vsamotyy@pk.edu.pl)

Department of Automatic Control and Information Technology, Cracow University of Technology

THE CORDIC METHOD OF CALCULATING THE EXPONENTIAL FUNCTION

METODA CORDIC OBLICZANIA FUNKCJI EKSPONENCJALNEJ

Abstract

This article presents a modern method of calculating the exponential function $\exp(x)$ based on the CORDIC iterative algorithm. The proposed solution is implemented in the form of a single iterative equation, which results in the simplification of the electronic version of this algorithm, thus reducing the cost of the device. It is important to point out that the accuracy of the calculation of the analysed function is not lost.

Keywords: exponential function, hybrid CORDIC method, LUT lookup table, iterative equations, activation functions

Streszczenie

W artykule zaproponowano nowoczesną metodę obliczania funkcji eksponencjalnej $\exp(x)$ na bazie algorytmu iteracyjnego CORDIC. Przedstawione rozwiązanie jest realizowane w postaci jednego równania iteracyjnego, co prowadzi do uproszczenia wersji elektronicznej tego algorytmu i w wyniku zmniejsza koszt urządzenia. Należy podkreślić, że przy tym nie tracimy na dokładności obliczania badanej funkcji.

Słowa kluczowe: funkcja eksponencjalna, hybrydowa metoda CORDIC, tablica odnośników LUT, równania iteracyjne, funkcje aktywacji

1. Introduction

CORDIC (coordinate rotation in a digital compute) algorithms were developed a long time ago; however, to this day they remain a subject of interest to many researchers. The method has been developed by Jack E. Volder [9]. The method can be easily used for fast Fourier transform calculations, Householder transformation calculations, digital signal filtering, image recognition, etc. The idea of this algorithm involves the application of the iterative process of rotating vectors on a plane at any angle – only shifting and adding operations are used. A number of patents has been published in which CORDIC algorithms are implemented in the form of electronic devices; however, only one of them features an electronic implementation of the exponential function [10]. This approach involves a large amount of computation and requires the electronic implementation of two iterative equations, which is a time-consuming process. There is a well-known paper on simplified exponential function calculation in which only two iterations are used [7, pp. 1–4]. This simplifies the electronic implementation of the CORDIC algorithm, although in the proposed approach, the number of calculations remains unchanged.

2. Calculating the exponential function using the hybrid CORDIC method

The device designed for calculating functions is

$$x = \exp(\pm\varphi), \quad (1)$$

Measurements of the input signal φ are converted into binary code (m – number of bits)

$$\varphi = \sum_{i=1}^m a_i 2^{-i}, \quad a_i = \{0,1\}, \quad \varphi \in [0,1] \quad (2)$$

The following well-known exponential function calculators [1-6, 8] use CORDIC iterative methods (Fig. 1):

$$x_{i+1} = x_i + \sigma_i y_i 2^{-i}, \quad (3)$$

$$y_{i+1} = y_i + \sigma_i x_i 2^{-i}, \quad (4)$$

$$z_{i+1} = z_i - \sigma_i \alpha_i, \quad (5)$$

$$\alpha_i = \arctan h(2^{-i}), \quad i = 1, 2, 3, 4, 5 \dots 12, 13, 13, 14, \dots, m, \quad (6)$$

$$\sigma_i = \begin{cases} -1 & \text{if } z_i < 0 \\ +1 & \text{if } z_i \geq 0 \end{cases}, \quad (7)$$

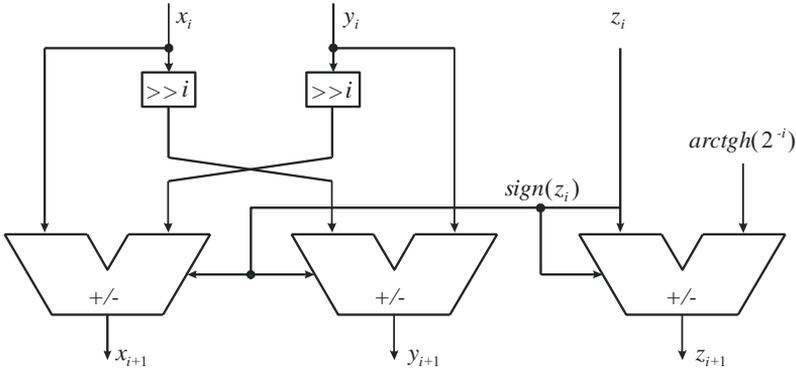


Fig. 1. Electronic implementation of the CORDIC method

$$x_1 = P', \quad y_1 = 0, \quad z_1 = \varphi, \quad x_{m+1} \approx \cosh(\varphi), \quad y_{m+1} \approx \sinh(\varphi), \quad \varphi \in [0, 1.118] \quad (8)$$

$$P'_{m1} = \prod_{i=1}^m \cosh(\alpha_i) = \prod_{i=1}^m \frac{1}{\sqrt{1-2^{-2i}}}; \quad P'_{m2} = \frac{1}{\sqrt{1-2^{-8}}} \frac{1}{\sqrt{1-2^{-26}}} \frac{1}{\sqrt{1-2^{-80}}} \quad (9)$$

$$P' = P'_{m1} P'_{m2} \quad (10)$$

After the completion of the iterative calculation of the function $y_{m+1} \approx \sinh(\varphi)$ and $x_{m+1} \approx \cosh(\varphi)$, we can calculate the exponent functions:

$$x_{m+1} + y_{m+1} \approx \exp(\varphi), \quad x_{m+1} - y_{m+1} \approx \exp(-\varphi) \quad (11)$$

The disadvantage of such devices is the redundancy of electronic components for the implementation of three iterative equations for variables x_{i+1} , y_{i+1} and z_{i+1} , and the resulting long calculation time (for a calculation with accuracy of m bits, we have to implement $m+2$ iterative cycles). The simplified device (Fig. 2) for the exponent calculation is described in [7]. The device implements the algorithm

$$w_{i+1} = w_i + \sigma_i w_i 2^{-i}, \quad z_{i+1} = z_i - \sigma_i \alpha_i, \quad w_1 = P', \quad z_1 = \varphi, \quad w_{m+1} \approx \exp(\varphi) \quad (12)$$

and

$$w_{i+1} = w_i - \sigma_i w_i 2^{-i}, \quad z_{i+1} = z_i - \sigma_i \alpha_i, \quad w_1 = P', \quad (13)$$

$$z_1 = \varphi, \quad w_{m+1} \approx \exp(-\varphi), \quad \varphi \in [0, 1.118] \quad (14)$$

Here, only two iterative equations are implemented for w_{i+1} and z_{i+1} , which simplifies the structure of the device. Unfortunately, this does not lead to a reduction in the number of calculations.

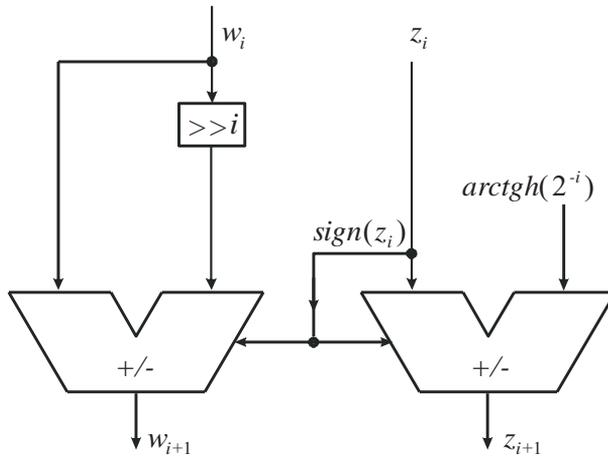


Fig. 2. Electronic implementation of the simplified CORDIC method

The end goal of our invention is to simplify the electronic implementation of the device and to reduce the number of calculation operations. First, let us consider the calculation of the function

$$x = \exp(+\varphi). \tag{15}$$

We propose dividing the input argument j into three distinct parts j_1, j_2, j_3 (Fig. 3)

$$\varphi = \varphi_1 + \varphi_2 + \varphi_3 \tag{16}$$

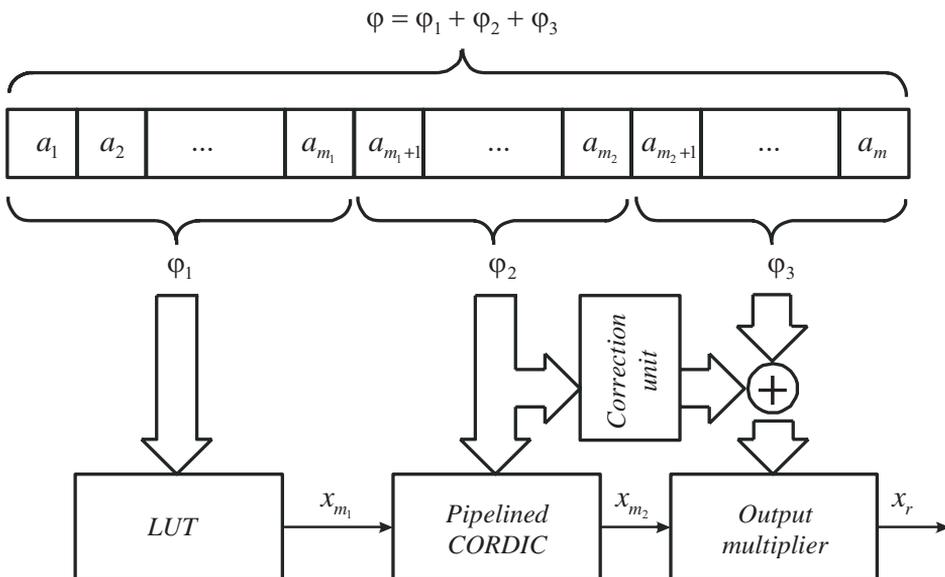


Fig. 3. Hybrid CORDIC

The first part j_1 occupies m_1 older bits of argument j . These are fed into the LUT lookup table (Fig. 3).

$$\varphi_1 = \sum_{i=1}^{m_1} a_i 2^{-i} \quad (17)$$

The second part (j_2) of the input argument j is computed using the CORDIC method, which is implemented in the form of a single iterative equation (Fig. 4). The second part (j_2) of the input argument j occupies the subsequent $m_2 - m_1$ bits

$$\varphi_2 = \sum_{i=m_1+1}^{m_2} a_i 2^{-i} \quad (18)$$

At the end, the third calculation block provides for the multiplication of the correction angle j_3 , which occupies $m - m_2$ bits

$$\varphi_3 = \sum_{i=m_2+1}^m a_i 2^{-i} \quad (19)$$

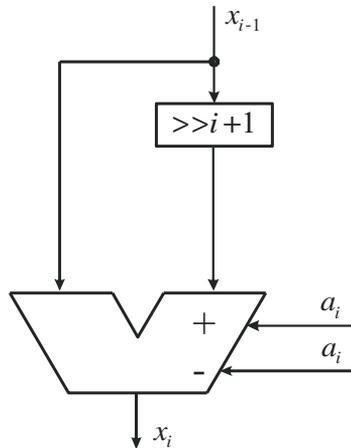


Fig. 4. Proposed pipelined CORDIC

Here, m_1 – the number of older bits of argument j , fed into the LUT table, which performs the function

$$x_{m_1} = P \cdot \exp(\varphi_1 + D_c) \quad (20)$$

where D_c and P – constants, which we calculate according to the formulas:

$$D_c = \sum_{i=m_1+2}^{m_2+1} \arctan h(2^{-i}) \quad (21)$$

$$P = \left(\prod_{i=m_1+1}^{m_2} \sqrt{1 - 2^{-2i-2}} \right)^{-1} \quad (22)$$

The values of x_{m_2} which we read from the LUT outputs, contain m bits. The minimum value of m_1 is obtained from the condition:

$$m_{1\min} = \left\lceil \frac{m-10-2 \cdot \log_2 3}{6} \right\rceil. \quad (23)$$

This quantity of older bits $m_{1\min}$ gives us the ability to maintain the accuracy of calculations in m bits. The upper limit of m_1 is limited by the value of m_2 and depends solely on the LUT memory space.

The bits of the φ_1 part, that is bits with numbers $m_1+1 \dots m_2$, are processed according to the CORDIC method. The value of m_2 is chosen based on the condition

$$m_2 = \left\lceil \frac{m}{2} \right\rceil \quad (24)$$

In practice, the CORDIC equations

$$b_i = 2 \cdot a_i - 1 \quad (25)$$

and

$$x_i = x_{i-1} + b_i \cdot x_{i-1} \cdot 2^{-i-1} \quad (26)$$

are implemented as follows:

$$\text{if } a_i=1, \text{ then } b_i=1 \text{ and } x_i = x_{i-1} + x_{i-1} \cdot 2^{-i-1}, \quad (27)$$

$$\text{if } a_i=0, \text{ then } b_i=-1 \text{ and } x_i = x_{i-1} - x_{i-1} \cdot 2^{-i-1}. \quad (28)$$

It follows that CORDIC contains only one iterative equation (28). The CORDIC output gives us the code x_{m_2} . In the final stage, we use the values of z corrected for the D_v component of φ_3 , which is calculated according to the formula

$$z = \varphi_3 + D_v, \quad (29)$$

where

$$D_v = \left(\sum_{i=m_1+1}^{m_2} a_i [2^{-i} - 2 \cdot \arctan h(2^{-i-1})] \right) \quad (30)$$

$$m_3 = \left\lceil \frac{m-5-\log_2 3}{3} \right\rceil. \quad (31)$$

$$x_r = x_{m_2} + z \cdot x_{m_2}. \quad (32)$$

A patented device can be used to calculate activation functions in neural networks – this gives the possibility for a significant reduction in the amount of computation in the network teaching process. There are three types of activation functions in which the exponential function is used. These include functions

$$\text{logistic } f_{\text{active}}(x) = \frac{1}{1 - e^{-x}}, \quad (33)$$

$$\text{hyperbolic } f_{\text{active}}(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}, \quad (34)$$

$$\text{exponential } f_{\text{active}}(x) = e^{-x}, \quad (35)$$

$$\text{softmax } f_{\text{active}}(x) = \frac{e^x}{\sum_i e^{x_i}}. \quad (36)$$

3. Conclusions

The characteristic feature of the patented device is that the argument j of function $y = \exp(\pm j)$ is divided into three parts and only the second part j_2 is calculated using the CORDIC iteration algorithm. This solution reduces the number of computations by several times and as a result, increases the speed of the device for calculating the function $y = \exp(\pm j)$.

The CORDIC algorithm is implemented in the proposed device in the form of only one iterative equation. This leads to the simplification of the electronic version of this algorithm and thus reduces the cost of the device.

The time pause in the patented device will be several times shorter than the currently known solution [10]. For example, for $m=32$ and $m_1=4$, the time pause in the patented device has 14 steps, and the current solution requires 34 steps. For $m=32$ and $m_1=8$, we have 10 and 34 steps, respectively.

References

- [1] Walther J.S., *A unified algorithm for elementary functions*, [in:] Proc. Spring Joint Comput. Conf., 1971, 379–385.
- [2] Walther J.S., *Elementary floating-point Cordic function processor and shifter*, US Patent 3766370, 1973.
- [3] Muller J.M., *Elementary functions: algorithms and implementation*. Birkhauser Boston, 2nd edition, 2006.
- [4] Hu X., Huber R., Bass S., *Expanding the Range of Convergence of the CORDIC Algorithm*, IEEE Transactions on Computers, Vol. 40, 1, 1991, 13–21.
- [5] Llamocca-Obregon D.R., Agurto-Rios C.P., *A Fixed-Point Implementation of the Expanded Hyperbolic CORDIC Algorithm*, Latin American Appl. res., Vol. 37, 1, 2007, 1–10.
- [6] Sudha J., Hanumantharaju M.C., Venkateswarulua V., Jayalaxmi H., *A Novel Method for Computing Exponential Function Using CORDIC Algorithm*, Procedia Engineering, 30, 2012, 519–528.

- [7] Pottathuparambil R., Sass R., *Implementation of a CORDIC based double-precision exponential core on an FPGA*, Proceedings of RSSI, 2008, 1–4.
- [8] Boudabous A., Ghozzi F., Kharrat M., Masmoudi N., *Implementation of hyperbolic functions using cordic algorithm*, in Proc. of the 16th Inter. Conf. on Microelectronics, 2004, 738–741.
- [9] Volder J.E., *The CORDIC Trigonometric Computing Technique*, IRE Transactions on Electronic Computers, 1959, 330–334.
- [10] Kantabutra V., *Apparatus For Computing Exponential And Trigonometric Functions*, United States Patent, US006055553A, Apr. 25, 2000.

Sergii Telenyk (stelenyk@pk.edu.pl)

Department of Automatic Control and Information Technology, Faculty of Electrical and Computer Engineering, Cracow University of Technology

Oleksandr Rolik

Eduard Zharikov

Department of Automation and Control in Technical Systems

Yevhenii Serdiuk

Department of Computer-Aided Management and Data Processing Systems, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

ENERGY EFFICIENT DATA CENTER RESOURCES MANAGEMENT

USING BEAM SEARCH ALGORITHM

ENERGOOSZCZĘDNE ZARZĄDZANIE ZASOBAMI CENTRÓW DANYCH ZA POMOCĄ ALGORYTMU WYSZUKIWANIA PROMIENIOWEGO

Abstract

Modern data centres consume large amounts of power resulting in high levels of carbon dioxide emission. The data centre is a virtual environment in which the workload is performed by virtual machines. A widely used technique to decrease data centre power consumption is to consolidate the virtual machines using a minimal number of physical servers. The authors propose a two-stage method to solve the virtual machine consolidation problem in cloud data centres. The proposed method is programmed in C# to evaluate it and to perform modelling using Google cluster-usage traces. The proposed method enables powering off nearly fifty percent of the previously selected physical servers by using an acceptable number of migrations of virtual machines.

Keywords: cloud computing, virtualisation, virtual machine consolidation, local beam search

Streszczenie

Nowoczesne centra danych zużywają duże ilości energii, co powoduje emisję dwutlenku węgla. Centrum danych reprezentuje zwirtualizowane środowisko, w którym obciążenie jest obsługiwane przez maszyny wirtualne. Powszechną techniką zmniejszania zużycia energii w centrach danych jest konsolidacja maszyn wirtualnych przy użyciu minimalnej liczby serwerów fizycznych. Autorzy proponują dwustopniową metodę rozwiązywania problemu konsolidacji maszyn wirtualnych w chmurowych centrach danych. Proponowana metoda jest zaprogramowana w języku C# w celu jej oceny i przeprowadzenia modelowania za pomocą śladów użycia klastrów Google. Proponowana metoda pozwala wyłączyć prawie 50% serwerów fizycznych wcześniej wybranych do wyłączenia przy użyciu dopuszczalnej liczby migracji maszyn wirtualnych.

Słowa kluczowe: chmura obliczeniowa, wirtualizacja, konsolidacja maszyn wirtualnych, lokalne wyszukiwanie promieniowe

1. Introduction

Providing a wide range of cloud information services is based on three main cloud service models: infrastructure as a service (IaaS); platform as a service (PaaS); software as a service (SaaS). The virtualisation of compute units, storage devices, networks, data warehouses, workplaces widely being implemented to more efficient use of data centre hardware.

The infrastructure as a service cloud service model allows to effectively use the hardware of the physical machine (PM) by virtualizing its local resources. In this case, the client is provided by part of the PM resources in the form of a virtual machine (VM). To provide modern information services, the client utilises one or more VMs of a specific configuration defined by the cloud service provider. Thus, there arises a set of tasks related to the management of virtual machines, physical servers, network interactions, storage devices, applications and other systems.

A separate VM or a container inside the VM is created for each instance of cloud application. In this paper, a VM with specific configuration is utilised for each application instance. Nowadays, the cloud service providers propose different configurations for VM instances. Moreover, based on certain business needs, the client can dynamically change the configuration of the VM or can customise load balancing, fault tolerance and backup capabilities. While the cloud service is working, the set of VMs is continuously changing by creating and deleting VMs to serve the changing workload. The number of VMs deployed on a separate PM can be changed in accordance with a client needs; therefore, some PMs become under loaded and, as a result, the power consumption of the data centre increases.

In order to use PM resources more effectively, the virtualisation tools provide the ability to migrate a VM from one PM to another. The impact of migration on the work of the VM is minimal, and VM migration is almost invisible to the client. It is known that the load on the physical servers that the VM is migrating between increases by 5–10 percent. One of the main tasks in managing the resources of the cloud data centre is to place VMs in such a way as to use fewer physical servers and reduce the number of virtual machine migrations.

The process of the redistribution of virtual machines among physical servers is referred to as the consolidation of the VMs. The solutions to the problem of VM consolidation have been presented in many publications [1], however, the virtualisation and cloud technologies available at that time are now outdated. In modern data centres, new hardware and system tools have been introduced and coexist with the previous generation of technologies. Thus, it is important to develop new algorithms and methods for managing the data centre resources in general, and the VM consolidation problem in particular.

In order to solve the VM consolidation problem, the authors propose a two-stage method based on the use of local beam search. The heuristics of the first and second stages of optimisation, the algorithm of the beam search, the evaluation function and the conditions for the completion of the algorithm are developed. Data relating to the Google cluster-usage traces was used for evaluation of the proposed method.

2. Related work

In recent years, several approaches and algorithms have been proposed to solve the VM consolidation problem with different objectives [1–3]. The problem of virtual machine consolidation is considered to be an optimisation problem with various objective functions. It can also be considered to be a multi-objective optimisation problem [4, 5]. The peculiarity of this problem is the presence of a large number of environmental conditions and constraints. In addition, the complexity is increased during the formulation of the objective function, which includes several indicators that need to be optimised. The simple management algorithms such as first-fit, best-fit and their modifications (Eucalyptus [6], Microsoft [7], Google [8]) are used in industrial data centres with cloud-based infrastructures for simplicity and robustness. This is due to the demands of the stable running of client applications and services. Moreover, the administrators are involved in the automated process of managing data centre resources through the continuous monitoring of virtual machines and services.

Researchers have proposed solutions that use objective functions such as minimising power consumption, minimising service quality violations, minimising network traffic by eliminating bottlenecks, and maximising productivity. One of the main conditions that need to be satisfied for modern clusters is the ability of the management algorithm to operate online [3]. Furthermore, it is possible to use optimisation methods that work when certain cluster conditions arise. In this case, new tasks are scheduled for the PMs that are not involved in the consolidation process.

In addition to traditional heuristics and deterministic algorithms, local search algorithms such as evolutionary algorithms [9], ant colony optimisation algorithms [10], tabu search [11], and simulated annealing [12] are used to solve the problem of VM consolidation. In our opinion, it is more effective to use the local search technique at the second stage of optimisation after preparing the appropriate set of states through deterministic algorithms in order to improve the solution found at the first stage.

In this paper, it is proposed to apply a local search on a data set obtained at the previous stage of the optimisation in order to reduce the number of migrations of the VMs and to increase the number of PMs being switched to 'sleep' mode.

3. Description of the system model

Nowadays, most services for clients are provided by cloud data centres. Cloud data centres are complex systems that consist of server subsystems, storage subsystems, network subsystems, and engineering subsystems.

In this paper, the authors consider the problem of managing a cluster of PMs as a subsystem of a data centre using virtualisation to provide utilizations of VMs requested by clients. To compose the cluster, two approaches are used – the use of heterogeneous configuration and use of the homogeneous configuration of PMs. Both approaches have their advantages and disadvantages. It is impossible to avoid heterogeneous configurations on the scale of a data

centre due to the evolution of the server core element and the new requirements of the users of IT infrastructure. This is why the configuration of PMs in each cluster may differ from the configuration of PMs in other clusters; however, the worst-case scenario is when the configuration of each PM in the cluster may differ.

The beam search algorithm is realized for a cluster, which consists of physical machines with different configurations. Each PM provides several resources for VMs deployed on it, such as: processor (CPU); memory capacity (RAM); access to the storage subsystem (IOPS); access to the network subsystem (NET). The number of VMs deployed on the PM depends on the available capacity of the PM resources, on the VM requirements for resources, on the time spent to run a task within the VM, and on the intensity of the flow of tasks. The number of VMs running on the PM is constantly changing. The change in the number of VMs occurs in the following states: the creation of a new VM, the removal of a VM, the migration of a VM.

The authors consider that the CPU and RAM resources of PMs may be allocated for VMs. However, the algorithm can be extended by taking into account other resources required by a VM. These two resources are chosen due to the use of input data from the Google cluster-usage traces (GCT) [13]. The machine events table and task events table from GCT have been used to study the operation of the beam search algorithm. Six thousand PMs were selected from the first table and seventy thousand tasks were randomly selected from the second table. For each PM from the machine events table, the following attributes are used: machine ID; CPU capacity; memory capacity. For each PM from the task events table the following attributes are used: task index within the job; machine ID; re-source request for CPU cores; resource request for RAM. The data in the tables are normalised with respect to the PM with the largest value of the capacity of each resource.

4. Description of the problem

The cluster is composed by a set P of M PMs and a set V of N VMs, $N, M \in \mathbb{N}$. During the management cycle of applying the beam search algorithm, the number of PMs and VMs does not change. Each task from the task events table is performed in a separate VM. In most cases the number of PMs and VMs between the management cycles may vary.

The required capacity of the j -th VM of resource k is denoted by $c_j^k \in (0,1]$, $k \in \{CPU, RAM\}$. The c_j^k is determined by the requirements of the task and is normalised with respect to the PM with the largest capacity of the resource k . The capacity of physical server i for resource k is denoted by $C_i^k \in (0,1]$. The C_i^k is determined by the type of PM and is normalised with respect to the PM with the largest capacity of the resource k .

In most cases the proposed model presumes the changes to the variables c_j^k and C_i^k during the lifetime of the VMs and the PMs. However, the model does not assume the changes to these variables during VM migration or during the management cycle. In the performed analysis, the constraints on the variables c_j^k and C_i^k are imposed by input data from the Google cluster-usage traces (GCT) [13]. Thus, the variables c_j^k and C_i^k are fixed during modelling.

The set P consists of a set A of physical machines that are defined to be switched to ‘sleep’ mode and a set B of physical servers that provide resources for VMs that will migrate from set A , $A \cup B = P$, from the PMs.

The migration of the virtual machine j to the physical machine i is denoted by $U_{ij} \in \{0,1\}$. The migration occurs if $U_{ij} = 1$. Each VM from V has its own ID associated with the number j during the management cycle of the algorithm. Each PM also has its own ID associated with the number i during the management cycle of the algorithm.

5. The method of VM consolidation based on the beam search algorithm

Description of the main algorithm

The input data of the beam search algorithm is set A of PMs and set B of PMs that have available resources. Thus, it is possible to allocate additional tasks on PMs from set B in the form of VMs. The number of PMs and VMs does not change during modelling.

The idea of the algorithm is to take the i -th PM from set A and search for such a PM or PMs from set B , that is ready to accept the j -th VM migrating from the i -th PM. If it is possible to switch all or part of the PMs from set A to sleep mode, then the matrix of migrations U_{ij} is obtained as a result of the management cycle.

Description of the beam search algorithm

The first stage is to prepare the input data for the second stage. The first stage involves obtaining set A of PMs to be released from the VM and set B of PMs for determining the migration plan.

The second stage is performed for each PM from set A :

- 1) At each step, any VM assigned to the i -th PM is selected and the following variants of migrations are considered:
 - a) migrating the given VM to another PM which has enough CPU and RAM resources
 - b) checking the possibility of exchanging the given VM with another VM from another PM under the condition that another VM requires fewer resources (in such a way, states with a better rate are considered and it is possible to avoid an endless loop) and, as a result, the other PM will not be overloaded after this exchange
- 2) selecting n (which is a width of the beam) exchanges with the highest rating from all possible exchanges
- 3) completing the search if the i -th PM has been released from the virtual machines or if it is impossible to construct new states because there are no options left to implement the admissible exchange a) or b)

The comparison of the states is performed using criterion (1):

$$J = \sum_{i=1}^m u_i^2 + \sum_{i=1}^n f_i^2 \quad (1)$$

where:

- u_i – the number of resources used on the i -th PM,
- f_i – the number of available resources on the i -th PM,
- m – the number of PMs in set B ,
- n – the number of PMs in set A .

Thus, the algorithm gradually reduces the number of resources used on each PM belonging to set A , and utilises the resources of PMs from set B .

The terms of completion of the algorithm

To complete the algorithm, the following conditions must be met:

- 1) the exhaustion of set A
- 2) the inability to migrate all VMs from a specified number of PMs, denoted as Th_A

If the second condition is not applied, the search cycles may run too long in comparison to the time spent on VM creation or compared to the time spent on VM migration when the VM has average requirements for memory resources. To determine Th_A , it is suggested to apply a heuristic that takes into account a certain percentage of physical servers from set A but not less than α physical servers. In the proposed algorithm, the values are accepted as follows, $Th_A = 0,05$, $\alpha = 10$. Using small values of α , the algorithm skips a significant number of PMs that could have been switched to sleep mode. Thus, as a result of the completion of the algorithm, those PMs were not released from the VMs running on them. This termination criterion is introduced to reduce the execution time of the algorithm.

Definition of input data (description of the first stage of the method)

The main task on the first stage of the method is to obtain a set of PMs as expectants to be switched to 'sleep' mode. It is proposed to obtain set A of PMs using two techniques – the lower boundary technique (LB) and the threshold of available resources technique (TAR). Let us consider each of the techniques in more detail.

The LB technique is used to determine the number of physical servers that cannot be switched to sleep mode after migration of all the VMs that run on them. Such an idea arises from the hypotheses used in the algorithm for determining the lower boundary.

The search of the lower boundary is performed as follows:

- 1) calculating the average resource volume for all PMs which host VMs,

$$\frac{1}{Q} \sum_{i=1}^Q C_i^k, 0 < Q \leq M - \text{the values for each resource } k \text{ are calculated separately}$$

- 2) calculating the sum of necessary resources for run of all the existing VMs for each

$$\text{resource separately, } \sum_{j=1}^R c_j^k, 0 < R \leq N$$

- 3) calculating the ratio of the required resources to the average resource volume and rounding off the values to a larger integer – the values for each resource k are calculated separately. The highest number obtained in this step will be the lower boundary
- 4) sorting the PMs in one of the following ways:
 - a) by the number of resources of the PM, then by the ratio of the used resources to the number of working VMs
 - b) by the number of resources of the PM, then by the number of assigned tasks, then by the ratio of used resources to the number of working VMs

As a result of detailed study of the algorithm, it has been revealed that option ‘b’ is significantly more effective. By applying option ‘b’ it was possible to switch 82 PMs to sleep mode; while applying option ‘a’ only 33 PMs could be switched to sleep mode using the same data set. As a result, the difference between the number of used PMs and the resulting lower boundary is calculated. The obtained number is the number of PMs of set A that may potentially be switched to the sleep mode. These PMs are the first in the sorted list of set A . The rest of the PMs go to set B .

The idea behind the TAR technique is the formation of set A in such a way that set A only contains PMs in which the total number of unused resources exceeds the amount of resources of one of the PMs in the cluster.

The threshold of available resources is denoted by β . Building set A using the threshold of available resources is performed as follows:

- 1) choosing the value β
- 2) selecting PMs which have more available resources than value β on each resource k
- 3) calculating the amount of free resources of selected PMs for each resource separately
- 4) sorting selected PMs similar to option ‘b’ from the lower boundary method
- 5) passing through sorted list of set A .

Until the sum of resources is greater than the volume of resources of the current PM, the algorithm deducts this volume from the sum, adds the current PM to the set A and proceeds to the next PM. Otherwise the algorithm stops passing through the sorted list of set A . Thus, set A is built. Set A contains PMs which must be switched to sleep mode. On the other hand, set B contains PMs for the exchange of virtual machines.

6. Evaluation of simulation results

The trace-driven experiments were conducted on fragments of the GCT [13] input data set. Data for testing and studying the proposed algorithm was selected from the GCT for a specific time range for which data was collected on a real cluster. This was necessary to take into account all data for the same period of time in the GCT tables. Seventy thousand tasks with specific requirements for resources k were randomly selected from the data set. Each created VM corresponds to one task from the data set. Six thousand physical servers were

selected from the data set where 5832 servers host VMs, and 168 servers do not host VMs, so they are available for hosting VMs. The width of the beam for the algorithm was chosen to be 5. The study of the influence of the beam width on the performance of the algorithm was performed in [14]. According to study [14], it is recommended to choose a beam width in the range 5-8, depending on the conditions of the method applications.

The proposed model has been implemented in C#. The simulations were conducted on the computer with an Intel i7-3632QM processor and 8 GB of RAM running Windows 10 Pro 64bit. The interface of the simulation program is shown in Fig. 1.

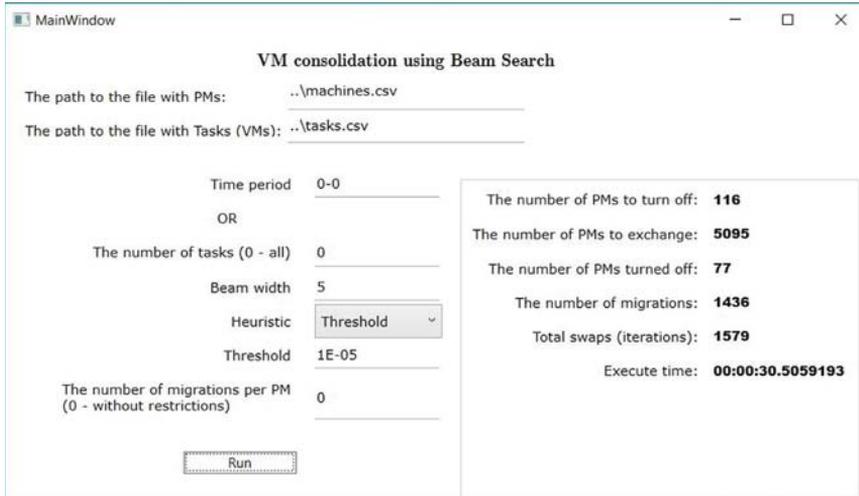


Fig. 1. The program interface

The first series of experiments were conducted without any limitation on the maximum number of simultaneous migrations per PM. Table 1 presents the simulation results of VM consolidation problem solving using the beam search algorithm with the threshold of available resources technique for different values of β . Table 2 presents the simulation results of VM consolidation problem solving using the beam search algorithm with the lower boundary technique.

The number of PMs switched to the sleep mode is denoted by PM_{sleep} . The number of VM migrations is denoted by VM_{mig} . The duration of solving the VM consolidation problem by the proposed algorithm is denoted by T . The number of PMs switched to sleep mode and the number of VM migrations are chosen as qualitative indicators of the proposed algorithm.

The effect of the threshold value β on the qualitative indicators of the algorithm performance is significant, as shown in Fig. 2 and Fig. 3. The dependence between the threshold value and the qualitative indicators of the algorithm performance was almost linear. The smaller the threshold, the more PMs are processed by the algorithm.

For $\beta=0$, some of the PMs (namely, those in which at least one resource is fully loaded) are not processed by the algorithm because when checking the availability of resources, strict inequality is used. For $\beta < 0,0002$, the algorithm with the TAR technique begins to work more efficiently and at the limit values, it works more effectively than the LB technique.

Table 1. Simulation results of solving the VM consolidation problem using the TAR technique

| β | B | A | PM_{sleep} | VM_{mig} | T. s |
|---------|------|-----|--------------|------------|--------|
| 0.005 | 199 | 3 | 0 | 0 | 0.034 |
| 0.004 | 299 | 3 | 0 | 0 | 0.052 |
| 0.003 | 1098 | 9 | 0 | 0 | 0.279 |
| 0.002 | 1393 | 10 | 0 | 0 | 0.38 |
| 0.001 | 1868 | 28 | 13 | 206 | 1.421 |
| 0.0009 | 1943 | 31 | 15 | 238 | 1.817 |
| 0.0008 | 2002 | 39 | 22 | 352 | 2.465 |
| 0.0007 | 2081 | 43 | 25 | 403 | 3.067 |
| 0.0006 | 2204 | 48 | 29 | 470 | 3.321 |
| 0.0005 | 2302 | 55 | 32 | 502 | 4.446 |
| 0.0004 | 2407 | 63 | 37 | 566 | 5.884 |
| 0.0003 | 2565 | 73 | 43 | 714 | 6.784 |
| 0.0002 | 2764 | 82 | 49 | 836 | 8.68 |
| 0.0001 | 3706 | 95 | 57 | 956 | 12.8 |
| 0.00005 | 4323 | 106 | 66 | 1128 | 18.422 |
| 0.00001 | 5095 | 116 | 77 | 1442 | 29.995 |
| 0 | 5328 | 125 | 82 | 1447 | 33.15 |

Table 2. Simulation results of solving the VM consolidation problem using the LB technique

| B | A | PM_{sleep} | VM_{mig} | T, s |
|------|-----|--------------|------------|-------|
| 5707 | 125 | 81 | 1435 | 32.13 |

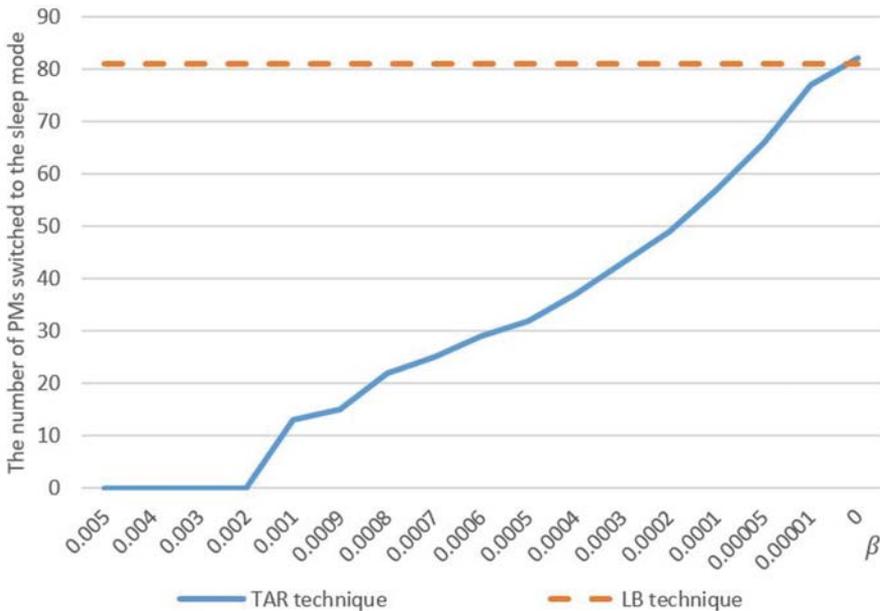


Fig. 2. The number of PMs switched to sleep mode

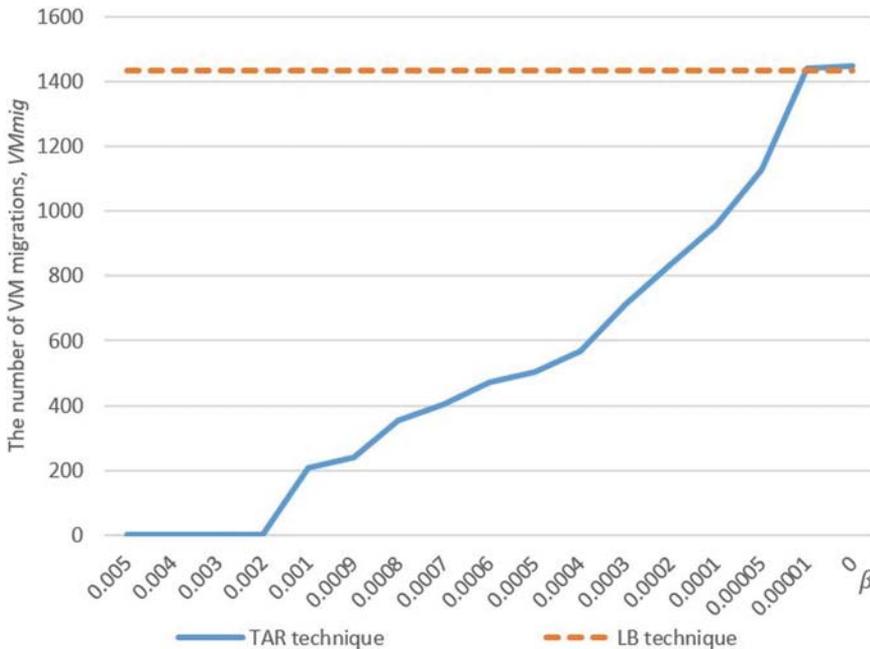


Fig. 3. The number of VM migrations

The advantage of using the TAR technique is the ability to adapt to the state of the cluster, taking into account such indicators as the state of other resources, the time of migration of the VM, and the intensity of incoming requests for the creation of new VMs.

An acceptable solution to the VM consolidation problem is possible when restrictions on the number of migrations as well as on the optimisation time are applied. The results show that the LB technique may take around 32 seconds to perform. Such performance may be impossible in production environments with dynamic VM management because the management system must take into account the dynamics of the new virtual machine deployment processes and the migration of virtual machines simultaneously.

To reduce the number of VM migrations, it is recommended to limit the maximum number of simultaneous migrations per PM. In production, hypervisors limit the maximum number of simultaneous migrations per PM, per network resource, and per datastore to provide a near 100 percent guarantee of no SLA violation during VM migrations [15]. On some workloads that are RAM intensive or on older hardware, a high number of simultaneous migrations (more than the recommended number) could saturate a system resource and result in downtime [16].

The second series of experiments were conducted with a limitation on the maximum number of simultaneous migrations per PM. This limitation starts to have an impact upon simulation results when the limit of simultaneous migrations per PM is 2. In production, the hypervisors are usually configured to a value in the range of 4-16, depending on the hardware [15]. The results show that the impact of this limitation appears when the number of PMs in set B is too small to accept VMs from the PMs in set A. In such cases, the PM_{sleep} decreases by around 40 percent.

Six data sets with different numbers of PMs and VMs were created using Google cluster-usage traces. The PMs and tasks were taken from different time ranges of the traces for an all-round check of the algorithm's operation. The obtained results show the same performance indicators as were obtained with the first configuration of the simulation environment.

7. Conclusion

In this paper, a two-stage method based on the beam search algorithm has been proposed in order to manage the process of virtual machine consolidation. The primary results of this paper are: the algorithm of the beam search for solving the VM consolidation problem under certain conditions; the heuristics of the first and the second stages of the algorithm; the evaluation function; the conditions for the completion of the algorithm; the consideration of constraints on the maximum number of simultaneous migrations per PM.

To evaluate the proposed method, the experiments were conducted on six fragments of the Google cluster-usage traces as an input data set. An analysis of the proposed techniques of the lower boundary and the threshold of the available resources was performed. As a result, it has been revealed that the technique with the threshold of available resources showed more efficient results while solving the VM consolidation problem. Moreover, the technique with the threshold of available resources allows adaptation to the state of the cluster, taking into account the state of other resources, the time of migration of the VM, the intensity of incoming requests for the creation of new VMs, and the limitation on the maximum number of simultaneous migrations per PM.

The benefit of the work is in the development of a two-stage method based on the algorithm of local beam search for solving the VM consolidation problem of the cloud-based data centre. The proposed method allows the turning off of almost 50 percent of the physical servers that are potentially configured to switch to sleep mode due to the use of a valid number of virtual machine migrations.

References

- [1] Lopez Pires F., Baran B., *A virtual machine placement taxonomy*, [in:] Proc. of the 15th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid), 2015, 159–168.
- [2] Ahmad R.W., Gani A., Hamid S.H.A., Shiraz M., Yousafzai A., Xia F., *A survey on virtual machine migration and server consolidation frameworks for cloud data centers*, Journal of Network and Computer Applications, Vol. 52, 2015, 11–25.
- [3] Telenyk S., Zharikov E., Rolik O., *An approach to virtual machine placement in cloud data centers*, [in:] Proc. of the 2016 International Conference Radio Electronics & Info Communications (UkrMiCo) 11–16 September, Kyiv, Ukraine, 2016, 1–6.

- [4] Lopez Pires F., Baran B., *Multi-objective virtual machine placement with service level agreement: A memetic algorithm approach*, [in:] Proceedings of the 2013 IEEE/ACM 6th International Conference on Utility and Cloud Computing, IEEE Computer Society, 2013, 203–210.
- [5] Saber T., Ventresque A., Brandic I., Thorburn J., Murphy L., *Towards a Multi-objective VM Reassignment for Large Decentralised Data Centres*, 2015 IEEE/ACM 8th International Conference on Utility and Cloud Computing (UCC), Limassol, 2015, 65–74.
- [6] *Eucalyptus community*, <http://open.eucalyptus.com> (access: 10.12.2017).
- [7] Lee S., Panigrahy R., Prabhakaran V., Ramasubrahmanian V., Talwar K., Uyeda L., Wieder U., *Validating heuristics for virtual machines consolidation*, Microsoft Research, MSR-TR-2011-9, 2011.
- [8] Sharma B., Chudnovsky V., Hellerstein J.L., Rifaat R., Das C.R., *Modeling and synthesizing task placement constraints in google compute clusters*, In Proceedings of the 2nd ACM Symposium on Cloud Computing (SOCC), 2011.
- [9] Mark C.C., Niyato D., Chen-Khong T., *Evolutionary optimal virtual machine placement and demand forecaster for cloud computing*, [in:] IEEE International Conference on Advanced Information Networking and Applications (AINA), 2011, 348–355.
- [10] Gao, Y., Guan, H., Qi, Z., Hou, Y., Liu, L., *A multi-objective ant colony system algorithm for virtual machine placement in cloud computing*, Journal of Computer and System Sciences, Vol. 79, No. 8, 2013, 1230–1242.
- [11] Ferreto, T., De Rose C., Heiss, H.U., *Maximum migration time guarantees in dynamic server consolidation for virtualized data centers*, [in:] Euro-Par 2011 Parallel Processing, Springer 2011, 443–454.
- [12] Wu Y., Tang M., Fraser W., *A simulated annealing algorithm for energy efficient virtual machine placement*, [in:] IEEE International Conference on Systems, Man, and Cybernetics (SMC), 2012, 1245–1250.
- [13] Reiss C., Wilkes J., Hellerstein J.L., *Google cluster-usage traces: format+ schema*, Google Inc., Mountain View, CA, USA, Technical Report, 2011.
- [14] Zharikov E., *Managing data center resources using heuristic search*, Problems in programming, Vol. 4, 2017, 16–27.
- [15] *Limits on Simultaneous Migrations*, <https://docs.vmware.com/en/VMware-vSphere/6.0/com.vmware.vsphere.vcenterhost.doc/GUID-25EA5833-03B5-4EDD-A167-87578B8009B3.html>, last accessed 2018/01/10 (access: 24.12.2017).
- [16] Telenyk S., Zharikov E., Rolik O., *Consolidation of Virtual Machines Using Stochastic Local Search*, Advances in Intelligent Systems and Computing, Springer, 2017, 523–537.

Adam Bednarz (adam.bednarz@pk.edu.pl)

Ludwik Byszewski (ludwik.byszewski@pk.edu.pl)

Institute of Mathematics, Faculty of Physics Mathematics and Computer Science,
Cracow University of Technology

AN ABSTRACT NONLOCAL FUNCTIONAL-DIFFERENTIAL SECOND ORDER
EVOLUTION CAUCHY PROBLEM

ABSTRAKCYJNE NIELOKALNE FUNKCJONALNO-RÓŻNICZKOWE
EWOLUCYJNE ZAGADNIENIE CAUCHY'EGO RZĘDU DRUGIEGO

Abstract

The aim of the paper is to prove two theorems on the existence and uniqueness of mild and classical solutions of a semilinear functional-differential evolution second order equation together with nonlocal initial conditions. The theory of strongly continuous cosine families of linear operators in a Banach space is applied. The paper is based on publications [1–12] and is a generalization of paper [7].

Keywords: nonlocal, second order, functional-differential, evolution Cauchy problem, Banach spaces

Streszczenie

W artykule udowodniono dwa twierdzenia o istnieniu i jednoznaczności całkowych i klasycznych rozwiązań semiliniowego funkcjonalno-różniczkowego zagadnienia ewolucyjnego Cauchy'ego rzędu drugiego z nielokalnymi warunkami początkowymi. W tym celu zastosowano teorię rodziny cosinus liniowych operatorów w przestrzeni Banacha. Artykuł bazuje na publikacjach [1–12] i jest uogólnieniem publikacji [7].

Słowa kluczowe: nielokalne, rzędu drugiego, funkcjonalno-różniczkowe, zagadnienie ewolucyjne Cauchy'ego, przestrzenie Banacha

1. Introduction

In this paper, we consider the abstract nonlocal semilinear functional-differential second order evolution Cauchy problem

$$u''(t) = Au(t) + f(t, u(t), u(a_1(t)), \dots, u(a_m(t)), u'(t)), \quad t \in (0, T], \quad (1.1)$$

$$u(0) = x_0, \quad (1.2)$$

$$u'(0) + \sum_{i=1}^p h_i u_i(t_i) = x_i, \quad (1.3)$$

where A is a linear operator from a real Banach space X into itself, $u: [0, T] \rightarrow X$, $f: [0, T] \times X^{m+2} \rightarrow X$, $a_i: [0, T] \rightarrow [0, T]$ ($i = 1, 2, \dots, m$), $x_0, x_i \in X$, $h_i \in \mathbb{R}$ ($i = 1, 2, \dots, p$) and

$$0 < t_1 < t_2 < \dots < t_p \leq T.$$

We prove two theorems on the existence and uniqueness of mild and classical solutions of the problem (1.1) - (1.3). For this purpose, we apply the theory of strongly continuous cosine families of linear operators in a Banach space. We also apply the Banach contraction theorem and the Bochenek theorem (see Theorem 1.1 in this paper).

Let A be the same linear operator as in (1.1). We will need the following assumption:

Assumption (A_1). Operator A is the infinitesimal generator of a strongly continuous cosine family $\{C(t) : t \in \mathbb{R}\}$ of bounded linear operators from X into itself.

Recall that the infinitesimal generator of a strongly continuous cosine family $C(t)$ is the operator $A : X \supset D(A) \rightarrow X$ defined by

$$Ax := \frac{d^2}{dt^2} C(t)x \Big|_{t=0}, \quad x \in D(A),$$

where

$$D(A) := \{x \in X : C(t)x \text{ is of class } C^2 \text{ with respect to } t\}.$$

Let

$$E := \{x \in X : C(t)x \text{ is of class } C^1 \text{ with respect to } t\}.$$

The associated sine family $\{S(t) : t \in \mathbb{R}\}$ is defined by

$$S(t)x := \int_0^t C(s)x ds, \quad x \in X, \quad t \in \mathbb{R}.$$

From Assumption (A_1), it follows (see [12]) that there are constants $M \geq 1$ and $\omega \geq 0$ such that

$$\|C(t)\| \leq Me^{\omega|t|} \quad \text{and} \quad \|S(t)\| \leq Me^{\omega|t|} \quad \text{for } t \in \mathbb{R}.$$

We also will use the following assumption:

Assumption (A₂). The adjoint operator A^* is densely defined in X^* , that is, $\overline{D(A^*)} = X^*$.

The paper is based on publications [1 - 12] and is a generalization of paper [7] in this sense that, now, a more general functional – differential problem is considered than in [7].

For convenience of the reader, a result obtained by J. Bochenek (see [3]) will be presented here.

Let us consider the Cauchy problem

$$u''(t) = Au(t) + h(t), \quad t \in (0, T], \quad (1.4)$$

$$u(0) = x_0, \quad (1.5)$$

$$u'(0) = x_1. \quad (1.6)$$

A function $u: [0, T] \rightarrow X$ is said to be a classical solution of the problem (1.4) – (1.6) if

$$u \in C^1([0, T], X) \cap C^2((0, T], X), \quad (a)$$

$$u(0) = x_0 \text{ and } u'(0) = x_1, \quad (b)$$

$$u''(t) = Au(t) + h(t) \text{ for } t \in (0, T]. \quad (c)$$

Theorem 1.1. *Suppose that:*

(i) *Assumptions (A₁) and (A₂) are satisfied,*

(ii) *$h: [0, T] \rightarrow X$ is Lipschitz continuous,*

(iii) *$x_0 \in D(A)$ and $x_1 \in E$.*

Then u given by the formula

$$u(t) = C(t)x_0 + S(t)x_1 + \int_0^t S(t-s)h(s)ds, \quad t \in [0, T],$$

is the unique classical solution of the problem (1.4) – (1.6).

2. Theorem on mild solutions

A function u belonging to $C^1([0, T], X)$ and satisfying the integral equation

$$u(t) = C(t)x_0 + S(t)x_1 - S(t) \left(\sum_{i=1}^p h_i u(t_i) \right)$$

$$+ \int_0^t S(t-s) f(s, u(s), u(a_1(s)), \dots, u(a_m(s)), u'(s)) ds, \quad t \in [0, T],$$

is said to be a mild solution of the nonlocal Cauchy problem (1.1) – (1.3).



Theorem 2.1. *Suppose that:*

- (i) *Assumption (A_1) is satisfied,*
(ii) $a_i: [0, T] \rightarrow [0, T]$ ($i=1, 2, \dots, m$) *are continuous on $[0, T]$, $f: [0, T] \times X^{m+2} \rightarrow X$ is continuous with respect to the first variable $t \in [0, T]$ and there exists a positive constant L_1 such that*

$$\|f(s, z_1, z_2, \dots, z_{m+2}) - f(s, \tilde{z}_1, \tilde{z}_2, \dots, \tilde{z}_{m+2})\| \leq L_1 \sum_{i=1}^{m+2} \|z_i - \tilde{z}_i\| \text{ for } s \in [0, T], \tilde{z}_i, z_i \in X$$

$$(i=1, 2, \dots, m+2),$$

(iii) $2C \left((m+1)TL_1 + \sum_{i=1}^p |h_i| \right) < 1,$

where $C := \sup \{ \|C(t)\| + \|S(t)\| + \|S'(t)\| : t \in [0, T] \},$

- (iv) $x_0 \in E$ and $x_1 \in X.$

Then, the nonlocal Cauchy problem (1.1) – (1.3) has a unique mild solution.

Proof. Let the operator $F: C^1([0, T], X) \rightarrow C^1([0, T], X)$ be given by

$$(Fu)(t) = C(t)x_0 + S(t)x_1 - S(t) \left(\sum_{i=1}^p h_i u(t_i) \right) + \int_0^t S(t-s) f(s, u(s), u(a_1(s)), \dots, u(a_m(s)), u'(s)) ds, \quad t \in [0, T].$$

Now, we shall show that F is a contraction on the Banach space $C^1([0, T], X)$ equipped with the norm

$$\|w\|_1 := \sup \{ \|w(t)\| + \|w'(t)\| : t \in [0, T] \}.$$

To do this, observe that

$$\begin{aligned} \|(Fw)(t) - (F\tilde{w})(t)\| &= \left\| S(t) \left(\sum_{i=1}^p h_i (\tilde{w}(t_i) - w(t_i)) \right) \right. \\ &+ \int_0^t S(t-s) \left(f(s, w(s), w(a_1(s)), \dots, w(a_m(s)), w'(s)) \right. \\ &\left. \left. - f(s, \tilde{w}(s), \tilde{w}(a_1(s)), \dots, \tilde{w}(a_m(s)), \tilde{w}'(s)) \right) ds \right\| \leq C \left(\sum_{i=1}^p |h_i| \right) \|w - \tilde{w}\| \\ &+ \int_0^t \|S(t-s)\| L_1 \left(\|w(s) - \tilde{w}(s)\| + \|w(a_1(s)) - \tilde{w}(a_1(s))\| + \right. \\ &\left. \dots + \|w(a_m(s)) - \tilde{w}(a_m(s))\| + \|w'(s) - \tilde{w}'(s)\| \right) ds \end{aligned}$$

$$\leq C \left((m+1)TL_1 + \sum_{i=1}^p |h_i| \right) \|w - \tilde{w}\|_1$$

and

$$\begin{aligned} \|(Fw)'(t) - (F\tilde{w})'(t)\| &= \left\| S'(t) \left(\sum_{i=1}^p h_i (\tilde{w}(t_i) - w(t_i)) \right) \right. \\ &\quad \left. + \int_0^t C(t-s) \left(f(s, w(s), w(a_1(s)), \dots, w(a_m(s)), w'(s)) \right. \right. \\ &\quad \left. \left. - f(s, \tilde{w}(s), \tilde{w}(a_1(s)), \dots, \tilde{w}(a_m(s)), \tilde{w}'(s)) \right) ds \right\| \leq C \left(\sum_{i=1}^p |h_i| \right) \|w - \tilde{w}\|_1 \\ &\quad + \int_0^t \|C(t-s)\| L_1 \left(\|w(s) - \tilde{w}(s)\| + \|w(a_1(s)) - \tilde{w}(a_1(s))\| + \dots + \|w(a_m(s)) - \tilde{w}(a_m(s))\| \right. \\ &\quad \left. + \|w'(s) - \tilde{w}'(s)\| \right) ds \leq C \left((m+1)TL_1 + \sum_{i=1}^p |h_i| \right) \|w - \tilde{w}\|_1, \quad t \in [0, T]. \end{aligned}$$

Consequently,

$$\|Fw - F\tilde{w}\|_1 \leq 2C \left((m+1)TL_1 + \sum_{i=1}^p |h_i| \right) \|w - \tilde{w}\|_1 \quad \text{for } w, \tilde{w} \in C^1([0, T], X).$$

Therefore, in space $C^1([0, T], X)$, there is the only one fixed point of F and this point is the mild solution of the nonlocal Cauchy problem (1.1) – (1.3). So, the proof of Theorem 2.1 is complete.

Remark 2.1. The application of a Bielecki norm in the proof of Theorem 2.1 does not give any benefit.

3. Theorem about classical solutions

A function $u: [0, T] \rightarrow X$ is said to be a classical solution of the problem (1.1) – (1.3) if

$$u \in C^1([0, T], X) \cap C^2((0, T], X), \quad (a)$$

$$u(0) = x_0 \quad \text{and} \quad u'(0) + \sum_{i=1}^p h_i u(t_i) = x_1, \quad (b)$$

$$u''(t) = Au(t) + f(t, u(t), u(a_1(t)), \dots, u(a_m(t)), u'(t)) \quad \text{for } t \in [0, T]. \quad (c)$$

Theorem 3.1. *Suppose that:*

- (i) Assumptions (A_1) and (A_2) are satisfied, and $a_i: [0, T] \rightarrow [0, T]$ ($i=1, 2, \dots, m$) are of class C^1 on $[0, T]$.

(ii) There exists a positive constant L_2 such that

$$\|f(s, z_1, z_2, \dots, z_{m+2}) - f(\tilde{s}, \tilde{z}_1, \tilde{z}_2, \dots, \tilde{z}_{m+2})\| \leq L_2 \left(|s - \tilde{s}| + \sum_{i=1}^{m+2} \|z_i - \tilde{z}_i\| \right)$$

for $s, \tilde{s} \in [0, T]$, $z_i, \tilde{z}_i \in X$ ($i=1, 2, \dots, m+2$).

(iii) $2C \left((m+1)TL_2 + \sum_{i=1}^p |h_i| \right) < 1.$

(iv) $x_0 \in E$ and $x_1 \in X.$

Then, the nonlocal Cauchy problem (1.1) - (1.3) has a unique mild solution u . Moreover, if

$$x_0 \in D(A), \quad x_1 \in E \quad \text{and} \quad u(t_i) \in E \quad (i=1, 2, \dots, p),$$

and if there exists a positive constant κ such that

$$\|u(a_i(s)) - u(a_i(\tilde{s}))\| \leq \kappa \|u(s) - u(\tilde{s})\| \quad \text{for } s, \tilde{s} \in [0, T] \quad (i=1, 2, \dots, m)$$

then u is the unique classical solution of nonlocal problem (1.1) - (1.3).

Proof. Since the assumptions of Theorem 2.1 are satisfied, the nonlocal Cauchy problem (1.1) - (1.3) possesses a unique mild solution, which is denoted by u .

Now, we shall show that u is the classical solution of problem (1.1) - (1.3).

Firstly, we shall prove that $u, u(a_i(\cdot))$ ($i=1, 2, \dots, m$) and u' satisfy the Lipschitz condition on $[0, T]$. Let t and $t+h$ be any two points belonging to $[0, T]$. Observe that

$$\begin{aligned} u(t+h) - u(t) &= C(t+h)x_0 + S(t+h)x_1 - S(t+h) \left(\sum_{i=1}^p h_i u(t_i) \right) \\ &\quad + \int_0^{t+h} S(t+h-s) f(s, u(s), u(a_1(s)), \dots, u(a_m(s)), u'(s)) ds \\ &\quad - C(t)x_0 - S(t)x_1 + S(t) \left(\sum_{i=1}^p h_i u(t_i) \right) \\ &\quad - \int_0^t S(t-s) f(s, u(s), u(a_1(s)), \dots, u(a_m(s)), u'(s)) ds. \end{aligned}$$

Since

$$C(t)x_0 + S(t) \left(x_1 - \sum_{i=1}^p h_i u(t_i) \right)$$

is of class C_2 in $[0, T]$, there are $C_1 > 0$ and $C_2 > 0$ such that

$$\left\| (C(t+h) - C(t))x_0 + (S(t+h) - S(t)) \left(x_1 - \sum_{i=1}^p h_i u(t_i) \right) \right\| \leq C_1 |h|$$

and

$$\left\| \left((C(t+h) - C(t))x_0 \right)' + \left((S(t+h) - S(t)) \left(x_1 - \sum_{i=1}^p h_i u(t_i) \right) \right)' \right\| \leq C_2 |h|.$$

Hence

$$\begin{aligned} & \|u(t+h) - u(t)\| \leq C_1 |h| \\ & + \left\| \int_0^t S(s) \left(f(t+h-s, u(t+h-s), u(a_1(t+h-s)), \dots, u(a_m(t+h-s))), u'(t+h-s) \right) \right. \\ & \quad \left. - f(t-s, u(t-s), u(a_1(t-s)), \dots, u(a_m(t-s))), u'(t-s) \right) ds \Big\| \\ & + \left\| \int_t^{t+h} S(s) \left(f(t+h-s, u(t+h-s), u(a_1(t+h-s)), \dots, u(a_m(t+h-s))), u'(t+h-s) \right) ds \right\| \\ & \leq C_1 |h| + \int_0^t M e^{\omega T} L_2 \left(|h| + \|u(t+h-s) - u(t-s)\| + \|u(a_1(t+h-s)) - u(a_1(t-s))\| + \dots \right. \\ & \quad \left. \dots + \|u(a_m(t+h-s)) - u(a_m(t-s))\| + \|u'(t+h-s) - u'(t-s)\| \right) ds + M e^{\omega T} N |h|, \end{aligned}$$

where

$$N := \sup \left\{ \left\| f(s, u(s), u(a_1(s)), \dots, u(a_m(s))), u'(s) \right\| : s \in [0, T] \right\}.$$

From this, we obtain

$$\|u(t+h) - u(t)\| \leq C_3 |h| + C_4 \int_0^t (\|u(s+h) - u(s)\| + \|u'(s+h) - u'(s)\|) ds. \quad (3.1)$$

Moreover, we have

$$u'(t) = \left(C(t)x_0 + S(t) \left(x_1 - \sum_{i=1}^p h_i u(t_i) \right) \right)' + \int_0^t C(t-s) f(s, u(s), u(a_1(s)), \dots, u(a_m(s))), u'(s) ds.$$

From the above formula, we obtain, analogously,

$$\|u'(t+h) - u'(t)\| \leq C_5 |h| + C_6 \int_0^t (\|u(s+h) - u(s)\| + \|u'(s+h) - u'(s)\|) ds. \quad (3.2)$$

By inequalities (3.1) and (3.2), we get

$$\|u(t+h)-u(t)\|+\|u'(t+h)-u'(t)\|\leq C\cdot|h|+C\cdot\int_0^t(\|u(s+h)-u(s)\|+\|u'(s+h)-u'(s)\|)ds.$$

From Gronwall's inequality, we have

$$\|u(t+h)-u(t)\|+\|u'(t+h)-u'(t)\|\leq\tilde{C}|h|, \quad (3.3)$$

where \tilde{C} is a positive constant.

By (3.3), it follows that $u, u(a_i(\cdot))$ ($i=1,2,\dots,m$) and u' satisfy the Lipschitz conditions on $[0,T]$. This implies that the mapping

$$[0,T]\ni t\rightarrow f(t,u(t),u(a_1(t)),\dots,u(a_m(t)),u'(t))\in X$$

also satisfies the Lipschitz condition.

The above property of f together with the assumptions of Theorem 3.1 imply, by Theorem 1.1 and by Theorem 2.1, that the linear Cauchy problem

$$v''(t)=Av(t)+f(t,u(t),u(a_1(t)),\dots,u(a_m(t)),u'(t)), \quad t\in[0,T],$$

$$v(0)=x_0,$$

$$v'(0)=x_1-\sum_{i=1}^p h_i u(t_i)$$

has a unique classical solution v such that

$$v(t)=C(t)x_0+S(t)\left(x_1-\sum_{i=1}^p h_i u(t_i)\right) \\ +\int_0^t S(t-s)f(s,u(s),u(a_1(s)),\dots,u(a_m(s)),u'(s))ds=u(t), \quad t\in[0,T].$$

Consequently, u is the unique classical solution of the semilinear Cauchy problem (1.1) – (1.3) and, therefore, the proof of Theorem 3.1 is complete.

References

- [1] Balachandran K., Ilamaram S., *Existence and uniqueness of mild and strong solutions of a semilinear evolution equation with nonlocal conditions*, Indian J. Pure Appl. Math. 25.4, 1994, 411–418.
- [2] Bednarz A., Byszewski L., *On abstract nonlocal Cauchy problem*, Technical Transactions, 1-NP/2013, 11–17.
- [3] Bochenek J., *An abstract nonlinear second order differential equation*, Ann. Polon. Math. 54.2, 1991, 155–166.
- [4] Bochenek J., *Cosine operator functions and condition (F)*, Selected Problems of Mathematics, Cracow University of Technology Monographs, Anniversary Issue 6, 1995, 13–24.
- [5] Bochenek J., Winiarska T., *Second order evolution equations with parameter*, Ann. Polon. Math. 59.1, 1994, 41–52.
- [6] Byszewski L., *On some application of the Bochenek theorem*, Univ. Jagel. Acta. Math. 45, 2007, 147–153.
- [7] Byszewski L., *An abstract nonlocal functional-differential second order evolution problem*, Technical Transactions 1/2017, 147–154.
- [8] Byszewski L., Winiarska T., *An abstract nonlocal second order evolution problem*, Opuscula Mathematica 32.1, 2012, 75–82.
- [9] Cholewa J.W., Dłotko T., *Global Attractors in Abstract Parabolic Problems*, London Mathematical Society Lecture Notes, Series 278, Cambridge University Press, Cambridge 2000.
- [10] Fattorini H. O., *Ordinary differential equation in linear topological spaces*, J. Differential Equations 5, 1968, 72–105.
- [11] Nagy B., *Cosine operator functions and the abstract Cauchy problem*, Periodica Math. Hungary 7, 1976, 213–217.
- [12] Travis C.C., Webb G.F., *Cosine family and abstract nonlinear second order differential equations*, Acta Math. Hungar. 32, 1978, 75–96.



Patrycja Bazan

Stanisław Kuciel (stask@mech.pk.edu.pl)

Institute of Material Engineering, Faculty of Mechanical Engineering, Cracow University of Technology

THE MECHANICAL CHARACTERIZATION OF COMPOSITES
BASED ON POLYOXYMETHYLENE AND THE EFFECT OF SILICONE ADDITION
ON THE MECHANICAL BEHAVIOUR OF MANUFACTURED COMPOSITES

CHARAKTERYSTYKA MECHANICZNA KOMPOZYTÓW
NA BAZIE POLIOKSYMETYLENU I WPLYW DODATKU SILIKONU
NA ZACHOWANIE MECHANICZNE WYTWORZONYCH KOMPOZYTÓW

Abstract

The mechanical properties of manufactured composites based on polyoxymethylene (Tarnoform 300) were determined. POM composites reinforced with ultra-high molecular weight silicon, thermoplastic polyurethane, and special chalk in order to reduce abrasiveness and aramid fibres were manufactured. The basic mechanical properties (tensile strength (σ_M), modulus of elasticity (E_t), strain at break (ϵ_B), flexural modulus (E_f) and flexural stress at 3.5% strain (σ_s)) were evaluated at three temperatures -20, 20 and 80°C. The density and Charpy impact of the produced composites were examined. In order to make reference to the effects of reinforcement and determine the characteristics of their microstructure SEM, images were taken.

Keywords: polyformaldehyde, additives, modification of structure, properties

Streszczenie

Określono właściwości mechanicznych kompozytów na podstawie polioksymetyleny Tarnoform 300. Wytworzono kompozyty wzmocnione silikonem o ultrawysokiej masie cząsteczkowej, termoplastycznym poliuretanem, kredą obniżającą ścieralność oraz włóknem aramidowym. Wyznaczono podstawowe właściwości mechaniczne (wytrzymałość na rozciąganie (σ_M), moduł sprężystości przy rozciąganiu (E_t), odkształcenie przy zerwaniu (ϵ_B), moduł sprężystości przy zginaniu (E_f) oraz naprężenie przy odkształceniu 3,5% (σ_s)) w trzech temperaturach -20, 20 and 80°C. Określono gęstość oraz udarność wg Charpy'ego dla wytworzonych kompozytów. W celu oceny efektów wzmocnienia i cech mikrostruktury wykonano mikrofotografie SEM.

Słowa kluczowe: poliformaldehyd, dodatki, modyfikacja struktury, właściwości

1. Introduction

Polyoxymethylene (POM) is a semicrystalline polymeric material. It is an engineering thermoplastic. POM is characterized by low friction and wear rate. It has an excellent balance of mechanical properties and it is chemically resistant to most solvents, chemicals and fuels at room temperature. Hence, such polymers are used to serve as an alternative to metals. Among the polymers obtained from the polymerization of aldehydes, POM is the only one that could reach commercial significance [1]. Additives on polyoxymethylene are used in order to easy processing (lubricating agents, processing aids, nucleating agents), performances (fillers, impact modifiers), lifetime increase (antioxidants, compounds reacting with secondary reaction products, UV stabilizers and flame retardants) and aspect properties (pigments). POM compounding can be relatively complex and additives are scarcely used alone, they react with each other and influence the properties [1]. Polymer composites based on POM matrices have been widely examined due to the fact that conventional materials no longer meet the needs and expectations of modern engineering. Chenghe Liu et al. [2] reported that using short basalt fibre as reinforcement POM enhances its mechanical properties. It was found that the 20wt.% fibre content increased the mechanical properties. The tensile strength was higher by 27.45%, impact strength increased by 9.65% and flexural strength by 18.11% with compared to pure POM. But its tribological properties were worse with the addition of the basalt fibres. Yatao Wang et al. [3] also studied composites based on POM but reinforced with long basalt fibre. The results obtained were similar. The addition of BF built up mechanical properties and impact strength, but tribological properties such as friction coefficient and wear rate dropped. However, thermal stability increased compared to unmodified POM. Wei Luo *et al.* [4] investigated the effect of morphology of aramid fibres and particles on the friction and wear of polyoxymethylene (POM)/ aramid composites under dry friction conditions. The results showed that the addition of short aramid fibres (ASF) and particles (AP) affected the friction and wear of POM composites with aramid in two different ways due to the presence of reinforcement in the composites. Mariola Wojciechowska et al. [5] examined the influence of different amounts of glass fibre (10-30wt.%) on the mechanical properties of POM composites. For composition with 30wt.% content of glass fibres the ultimate tensile strength exhibited elevation by 96% but also deterioration in elongation after break. The impact strength and hardness also increased nearly 100% and 40%, respectively. The mechanical and tribological properties of the polyoxymethylene (POM) composite reinforced with carbon fibre (5-25vol%) were investigated. The tensile strength and modulus rose with increasing volume fraction. It was also observed that the friction coefficient for carbon fibre reinforced POM was lower than pure POM [6]. Natural fibres are also widely used as reinforcement of POM composites [7-10], for example the mechanical and physical characteristic of composites composed of polyacetal and cellulose were investigated in [11-13] the POM/CeF composites possessed high modulus, stiffness and had low wear rate. The results of SEM observation indicated good interfacial adhesion between the monofilaments of the CeF and the POM matrices during the fracture process. Afsaneh Fakhar et al. [14] investigated the tribological properties of polyoxymethylene (POM) composites with aramid fibres (20wt.%) and PTFE (13wt.%). The results showed that both of additives reduced the

coefficient of friction and abrasive wear of the material but also reduced the breaking energy which eliminated the role of abrasive wear in the conditions. The influence of adding copper and PTFE particles on thermal conductivity and tribological properties of POM composites was determined by Junqing He et al. [15–16]. The results showed that the addition of 3% by weight of Cu to polyoxymethylene had little effect on thermal conductivity and slightly decreased the coefficient of friction and abrasion rate, while the PTFE addition significantly reduced both friction coefficient and material wear. Composites are present in a wide variety of industries and technologies, but this does not slow down the work rate on new materials. The aim of this study is investigation of the effect of silicon addition, aramid fibre and thermoplastic polyurethane on mechanical properties of POM composites as a first stage of investigation of the tribo-mechanical behaviour of manufactured composites.

2. Experimental part

2.1. Materials and methods

The standard dumbbell samples and bars were made at the Plastics Laboratory of Azoty Group SA in Tarnow using the Engel ES 200/40 HSL injection moulding machine at temperatures indicated by the manufacturer for Tarnoform T-300. The granules of the composition were prepared by twin-screw extrusion with cold granulation using a line of compounding. The selected and manufactured materials which were used for the study are presented in Table 1.

Table 1. Description of manufactured and examined materials

| Index | Additives | Description |
|---------|--|--|
| POMSM | 95wt.% Tarnoform 300 (POM) + 5wt.% Dow Corning MB40-006 Masterbatch- | polyoxymethylene (POM) with an ultra-high molecular weight silicone additive |
| POMSO | 100wt.% Tarnoform 300 SO NAT | ready mix in the form of POM granules with silicone for injection to reduce friction coefficient and abrasion in plastic-plastic systems |
| POMAR | 80wt.% Tarnoform 300 + 10wt% Aramid fiber | ready mix polyoxymethylene with aramid fibre to improve abrasion resistance and reduce coefficient of friction |
| POM2U | 80.wt% Tarnoform 300 (POM) + 20wt.% TPU | polyoxymethylene (POM) with the addition of thermoplastic polyurethane to improve the damping of mechanical vibrations and noise reduction |
| POMBK5M | 95wt.% Tarnoform 300 BK + 5wt.% Dow Corning MB40-006 Masterbatch | polyoxymethylene with addition of special chalk and silicone lubricant to reduce abrasion |

2.2. Method of testing

The basic physical and mechanical tests of polyacetal composites were accomplished. Density was estimated by the hydrostatic method using a RADWAG WAS 22W scale. The mechanical properties were tested by a static tensile test (PN-EN ISO 527-1:20100) and the three point flexural tests according to the PN-EN ISO 178:2011 standard. Measurements were obtained using an MTS Criterion Model 45 universal testing machine, with a measuring range up to 30 kN using the MTS axial extensometer. The test speed was set up to 10mm/min. The mechanical properties, such as tensile modulus, tensile strength, strain at break as well as flexural modulus and flexural strength were determined. A Charpy impact test (PN-EN ISO 179-1:2010) was examined on unnotched specimens using a Zwick HIT 5.SP. The microstructure observations were made on the gold-sputtered tensile-test fracture surfaces of specimens with the use of a Scanning Electron Microscope JEOL JSN5510LV. The values were obtained from an average at least of 5 specimens.

3. Results and discussion

The mechanical properties are affected by many factors, such as: temperature, time and speed of deformation, duration of the test, and geometry of the samples. The obtained results are presented in Figures 1–2. The determined parameters are summarized in Table 2.

Table 2. Mechanical properties of the tested materials

| Sample | Density [g/cm ³] | Tensile strength [MPa] | Tensile modulus [MPa] | Strain at break [%] | Flexural strength at 3,5% of stain [MPa] | Flexural modulus [MPa] | Impact Strength [kJ/m ²] |
|----------|------------------------------|------------------------|-----------------------|---------------------|--|------------------------|--------------------------------------|
| POMT300* | 1.410 | 62 | 2800 | 50 | 61 | 2500 | 200 |
| POM5M | 1.401 | 54.0 ± 0.5 | 2966 ± 102 | 37 ± 11.5 | 80.9 ± 1.8 | 2719 ± 37 | 96.5 ± 14.7 |
| POMSO | 1.400 | 51.3 ± 0.7 | 2894 ± 82 | 37.8 ± 3.8 | 77.9 ± 0.4 | 2645 ± 5 | 176.1 ± 11.4 |
| POMAR | 1.413 | 70.4 ± 0.2 | 3821 ± 458 | 5.5 ± 0.2 | 92.1 ± 3.4 | 3286 ± 264 | 51.5 ± 5.4 |
| POM2U | 1.360 | 41.3 ± 8 | 1841 ± 306 | 63.0 | 50.4 ± 0.8 | 1713 ± 52 | not break |
| POMBK5M | 1.426 | 51.3 ± 0.8 | 3105 ± 118 | 41.5 ± 8.5 | 82.8 ± 1.5 | 2947 ± 47 | 105.9 ± 13.9 |

* Data of manufacturer of Tarnoform T300

The addition of silicone or aramid fibre does not have a substantial influence on the density of the produced composites, only the addition of thermoplastic polyurethane reduce the density by 20% which is proportional to the mass fraction.

Analysing the results from the static tensile test (Figure 1), a rise in deformations for the composition with the addition of polyurethane can be observed, as well as a reduction for this composition which is reinforced with aramid fibre while the other compositions show similar strains at break. Two tendencies can be indicated: a significant (over 30%) increase in the strength and modulus for aramid fibre-reinforced composites and a similar decrease, in particular the modulus of elasticity for the composition with polyurethane.

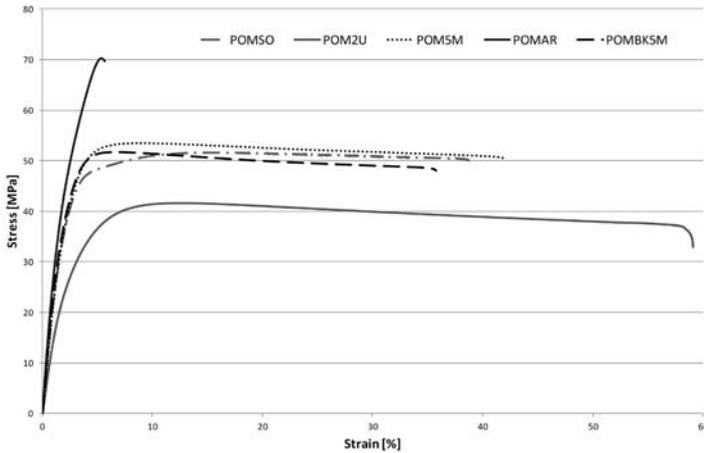


Fig. 1. Tensile stress-strain curves for the tested composites

A comparison of the static bending test's charts for the tested composites is presented in Figure 2. The curves indicate that bending properties change with a marked diminish for the composition with polyurethane. The slight variation of the module between the compositions with aramid fibre and the others compositions may indicate a lower adhesion between the aramid fibres and the polyacetal matrix.

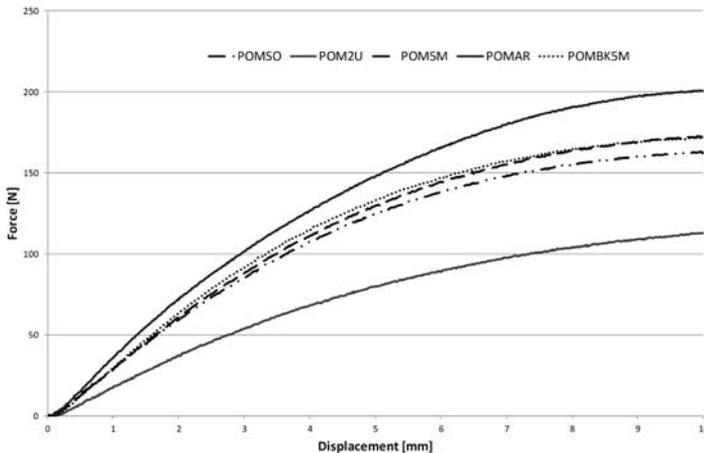


Fig. 2. Bending force-displacement curves for the tested composites

Analysis of mechanical properties at three temperatures demonstrates that the properties at lower temperature build up quite proportionally due to the fact that the glass transition temperature for polyacetal is around -50 C°. However, at elevated temperatures, a substantial stiffness-loss and a slight decline of tensile strength can be observed. The comparison is shown in Figure 3 and 4.

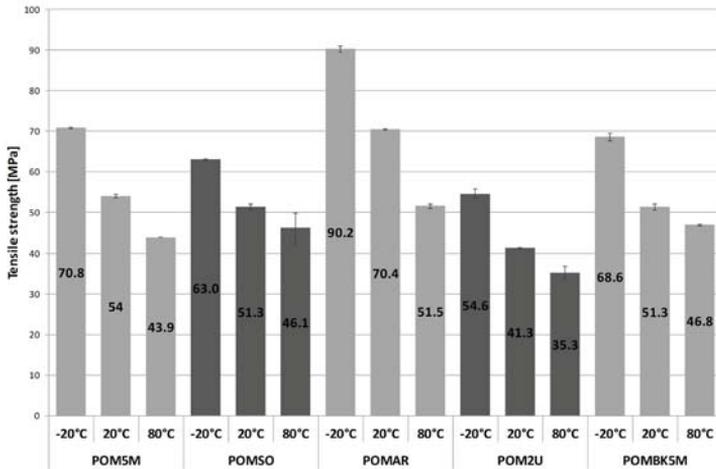


Fig. 3. The effect of temperature on tensile strength of tested composites

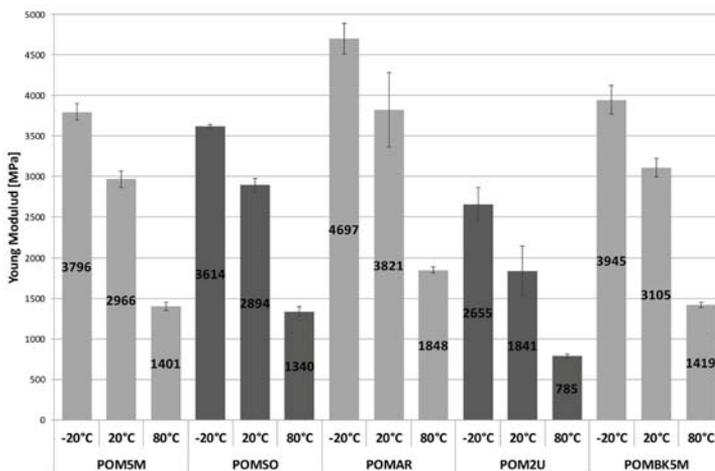
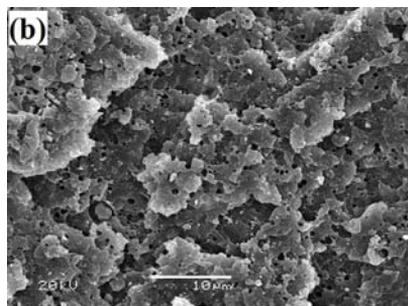
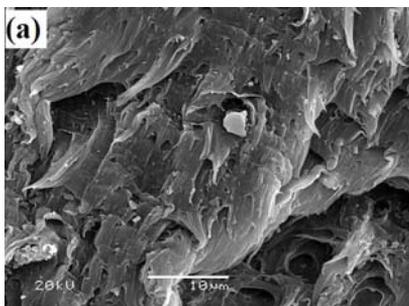


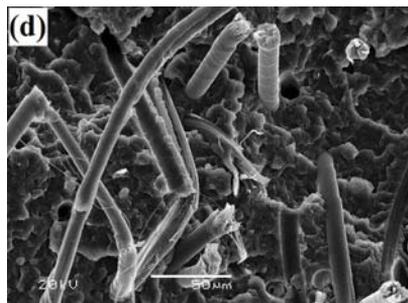
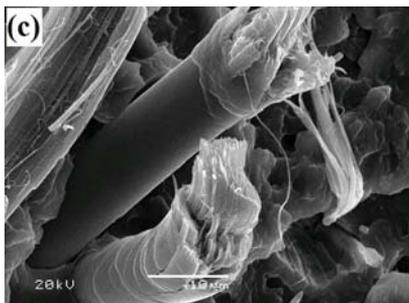
Fig. 4. The effect of temperature on tensile modulus of tested composites

It is worth noticing that the addition of siloxane oil slightly reduces the resistance to temperature. Directed measurements showed that elevated temperature lowers the possibility of strengthening the composite with aramid fibres (almost 30%), while the stiffness is still high – this is understandable due to the polymeric nature of this fibre. Conversely, in the case of a composite with the addition of polyurethane while the tensile strength slightly decreases (about 15%), the impact of elevated temperature on the tensile modulus is easily visible, a high temperature causes almost 60% diminishment in Young’s modulus. A comparison of strength and tensile modulus at reduced temperatures demonstrates a decreasing effect of reinforcement with aramid fibre. The tensile modulus and tensile strength for composition with thermoplastic polyurethane increase 44% and 30%, respectively.

POMBKSM at (a) 2000x
and (b) 1000x magnification.



POMAR at (c) 2000x and (d)
500x magnification



POMSO at (e) 2000x and (f)
1000x magnification

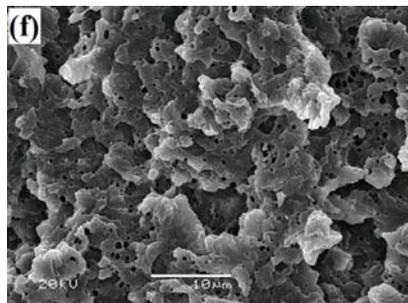
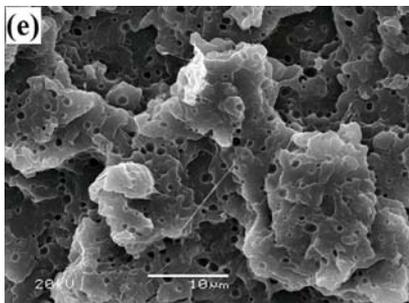
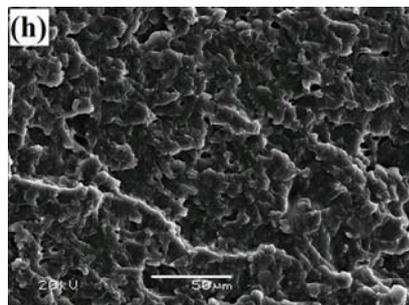
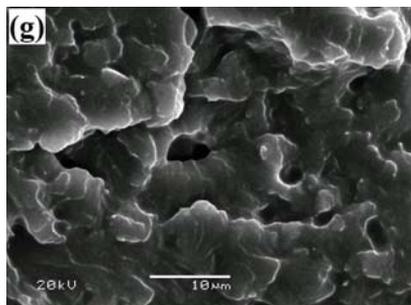
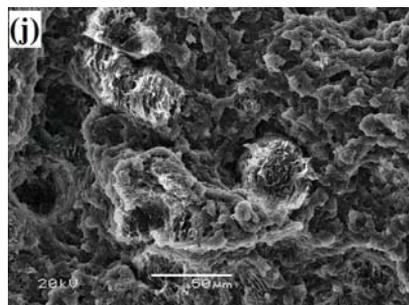
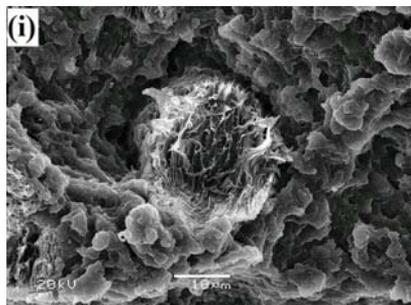


Fig. 5. SEM micrographs of tensile fractured surfaces of tested composites

POM5M at (g) 1000x and
(h) 500x magnification



POM2U at (i) 1000x and (j)
250x magnification



Cont. fig. 5. SEM micrographs of tensile fractured surfaces of tested composites

Figure 5 presents the microstructures of the tested materials. In the microstructure images of the POMBKSM composite microparticles of silicon oil (black holes with a diameter about 1–2 μm) can be observed as well as a few larger chalk particles (2–3 μm), which are evenly distributed in the polyacetal matrix. Images of POMAR show a modified polyacetal with aramid fibres. The micrographs confirm the aramid fibres with a diameter about 12.5 μm which present a well-developed surface. SEM images of POM5M show that siloxan creates small areas of crystallinity and they disperse in the form of holes with 2–6 μm in diameter. Microstructures of POM with the addition of a silicon that reduces the coefficient of friction (POMSO), create images similar to POM5M, however, the oil forms are more irregular and larger (1–4 μm). The microstructure of polyacetal with thermoplastic polyurethane (POM2U) clearly shows its two-phase nature and very good mixing of both components of the composition

4. Conclusion

The study allowed the mechanical properties of compositions based on polyacetal to be determined. The properties show that the addition of silicones cause an increase in the flexural tensile as well as a flexural and tensile modulus with a slight decrease in the tensile strength. Only the addition of aramid fibres causes an increase in tensile strength. The addition of 20% of thermoplastic polyurethane lowers tensile and flexural properties.

Comparison of the results obtained after the static tensile test at three temperatures proved that properties build up proportionally at lowered temperature and tend to slightly drop off at elevated temperatures. The addition of siloxane oil slightly reduces the resistance to temperature. Aramid fibre used as a reinforcement saves high stiffness of POM composites at elevated temperature while the addition of thermoplastic polyurethane may maintain tensile strength at an acceptable level. In the microstructure images of the POM composite with the addition of silicon irregular microparticles of silicon oil with a diameter about 1–6 μm can be observed. The microstructure of polyacetal with thermoplastic polyurethane shows its two-phase nature and the very good mixing of both components in the composition.

References

- [1] Lüftl S., Visakh P.M., Chandran S., *Polyoxymethylene Handbook: Structure, Properties, Applications and their Nanocomposites*, Scrivener Publishing LLC, New Jersey 2014.
- [2] Liu C., Long C., Chen L. et al., *Mechanical and tribological properties of short basalt fiber-reinforced polyoxymethylene composites*, Polymer (Korea) 40/2016, 836–845.
- [3] Wang Y., Wang X., Wu D., *Mechanical and tribological enhancement of polyoxymethylene-based composites with long basalt fiber through melt pultrusion*, Composite Interfaces 23/2016, 743–761.
- [4] Luo W., Ding Q., Li Y. et al., *Effect of Shape Morphology on Mechanical, Rheological and Tribological Properties of Polyoxymethylene/Aramid*, Composites Polymer Science, Ser. A 57/2015, 209–220.
- [5] Wojciechowska M., Kwiatkowski D., Tuzikiewicz W., *Wpływ włókna szklanego na właściwości mechaniczne i krystaliczność kompozytów POM i PA6*, Przetwórstwo tworzyw 5/2014, 462–467.
- [6] Tian Y. Q., Huo J. L., *The mechanical and tribological properties of carbon fiber reinforced POM composites*, Applied Mechanics and Materials 182–183/2012, 135–138.
- [7] Gañán P., Mondragon I., *Effect of Fiber Treatments on Mechanical Behavior of Short Fique Fiber-reinforced Polyacetal Composites*, Journal of Composite Materials 39/2005, 633–646.
- [8] Li W., Xiang D. H., Lu Y. et al., *Effects of Concentration of Alkaline Treated SF on the Tribological Properties of POM Composites Filled with LDPE and Sisal Fibers*, Advanced Materials Research 415–417/2012, 94–99.
- [9] Dan-Mallam Y., Abdullah M.Z., Yusoff P. S.M.M., *Influence of Recycling Frequency on Mechanical and Physical Properties of Kenaf Fiber Reinforced Polyoxymethylene Composite*, Journal of Natural Fibers 13/2016, 532–546.
- [10] Espinach F. X., Granda L. A., Tarres Q. et al., *Mechanical and micromechanical tensile strength of eucalyptus bleached fibers reinforced polyoxymethylene composites*, Composites Part B: Engineering 116/2017, 333–339.
- [11] Bledzki A. K., Mamuna A. A., Feldmann M., *Polyoxymethylene composites with natural and cellulose fibres: Toughness and heat deflection temperature*, Composites Science and Technology 72/2012, 1870–1874.

- [12] Kawaguchi K., Mizuguchi K., Suzuki K. et al., *Mechanical and Physical Characteristics of Cellulose-Fiber-Filled Polyacetal Composites*, Journal of Applied Polymer Science 118/2010, 1910–1920.
- [13] Porebska R., Rybak A., Kozub B. et al., *Polymer matrix influence on stability of Wood polymer composite*, Polymers for Advanced Technologies 26/2015, 1076–1082.
- [14] Fakhar A., Razzaghi-Kashani M., Mehranpour M., *Improvements in tribological properties of polyoxymethylene by aramid short fiber and polytetrafluoroethylene*, Iranian Polymer Journal 22/2013, 53–59.
- [15] He J., Zhang L., Li C. et al., *The Effects of Copper and Polytetrafluoroethylene (PTFE) on Thermal Conductivity and Tribological Behavior of Polyoxymethylene (POM) Composites*, Journal of Macromolecular Science, Part B: Physics 50/2011, 2023–2033.
- [16] He J., Zhang L., Li C., *Thermal Conductivity and Tribological Properties of POM-Cu Composites*, Polymer engineering and science 50/2010, 2153–2159.

Stefan Chwastek (chwastek@mech.pk.edu.pl)

Faculty of Mechanical Engineering, Cracow University of Technology

SELECTED ASPECTS INVOLVED IN THE OPTIMIZATION OF CRANES WITH PIVOTING BOOMS

WYBRANE ZAGADNIENIA OPTYMALIZACJI ŻURAWI Z WYCHYLNĄ WYSIĘGNIKIEM

Abstract

Certain crane operations – hoisting/lowering the payload connected to a slewing jib – require a nonlinear description to take Euler and Coriolis forces into account, the impacts of which should already be minimised at the stage of selection of the system parameters and mechanism structure. Optimal sets of parameters for the crane mechanisms thus obtained were optimised for the full range of slewing motion. It is demonstrated that the selection of the geometric dimensions of the structural elements of the hoisting mechanisms, i.e. the slewing system and counterbalances, enables the horizontal track error load to be minimised whilst the forces acting on the mechanism and inducing its vertical movement can be reduced. Thus, for the assumed lifting capacity and distance jaunt we get the structure of the crane mechanism that guarantees the minimal consumption of energy.

Keywords: cranes, counterbalance, pivoting jib, slewing system, Euler's forces, Coriolis forces, energy consumption, nonlinear and non-stationary differential equations of motion, vibration, parametric optimisation, horizontal track error load, one-link jib crane

Streszczenie

Niektóre operacje żurawi: podnoszenie/opuszczanie ładunku połączone ze zwodzeniem wysięgnika wymagają nieliniowego opisu, biorąc pod uwagę siły Eulera i Coriolisa, których wpływ powinien być minimalizowany już na etapie doboru struktur i parametrów mechanizmów. Uzyskane w ten sposób optymalne zestawy parametrów mechanizmów żurawia zostały zoptymalizowane dla pełnego zakresu ruchu zwodzenia. Jak wykazano w pracy, poprzez właściwy dobór wymiarów geometrycznych elementów konstrukcji żurawia tworzących mechanizmy linowe: wypadu i przeciwwagi możliwe jest uzyskanie minimum błędu prostowodności poziomej toru ładunku oraz minimalizacja sił w mechanizmie zwodzenia. W efekcie dla założonych: udźwignięć i odległości wypadu otrzymujemy struktury mechanizmów żurawia gwarantujące najmniejsze zapotrzebowanie energii.

Słowa kluczowe: żurawie, przeciwwaga, wychylny wysięgnik, układ zwodzenia, siły Eulera, siły Coriolisa, zużycie energii, nieliniowe i niestacjonarne równania ruchu, drgania, optymalizacja parametryczna, błąd prostowodności poziomej, żuraw z wychylnym wysięgnikiem

1. Introduction

This study investigates the energy efficiency of jib lift mechanism structures with unilateral constraints (rope/cable mechanisms) optimized together with the jib-balancing mechanism.

Previous works on this subject [2, 3] were limited in scope as the analysis was mostly restricted to a few selected boom positions. More recent works such as [6, 7] focused on the search for the optimal position of blocks in a compensation mechanism such that the boom's unbalanced moment can be minimized. In work [6], a minimum deviation of the vertical load is sought for a finite number of boom positions, based on the linearised form of the objective function.

A similar problem (trajectory optimization) is investigated in [7] with respect to the trajectory optimization of a double-rocker four-bar mechanism.

Cranes with a pivoting jib are complex dynamic systems governed by nonlinear, non-stationary differential equations of motion [4, 5].

The study investigates the behaviour of a crane with a pivoting jib (the physical model of which is shown in Fig. 1) subjected to the applied loads: Q – lifting load due to hoisted mass, G_p – counterweight and G_w – weight of the jib. Respective forces acting on the ropes due to the lifting load – S_Q jib lifting – S_w counterweight – S_p act at acute angles to the jib: α, β, γ – not indicated in Fig. 1.

The physical model of a one-link crane is governed by the following equations of motion:

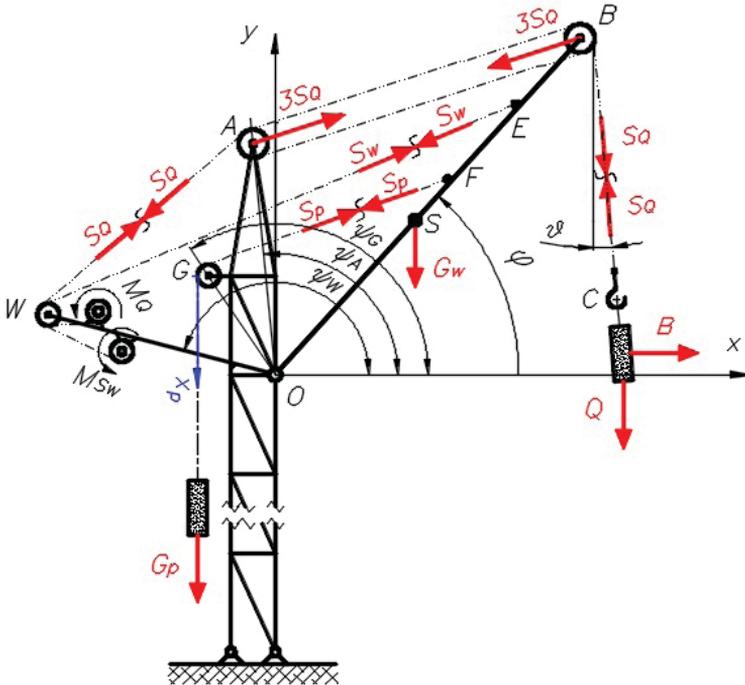


Fig. 1. Physical model of a one-link crane

$$\left\{ \begin{array}{l} J_{WO} \varepsilon_{\phi} = L_{OB} \left[3 \cdot \sin(\alpha) \cdot S_Q - \cos(\phi - \nu) \cdot S_Q + \kappa_{OE} \cdot \sin(\beta) \cdot S_W + \kappa_{OF} \cdot \sin(\gamma) \cdot S_P - \kappa_{OS} \cdot \cos(\phi) \cdot G_W \right] \\ m_Q \left[a_{BC} - L_{BC} \cdot \omega_{\nu}^2 - L_{OB} \sin(\phi - \nu) \cdot \varepsilon_{\phi} + L_{OB} \cos(\phi - \nu) \cdot \omega_{\phi}^2 \right] = \cos(\nu) \cdot Q - S_Q \\ m_Q \left[L_{BC} \cdot \varepsilon_{\nu} + 2 \cdot \omega_{\nu} \cdot v_{BC} - L_{OB} \cos(\phi - \nu) \cdot \varepsilon_{\phi} - L_{OB} \sin(\phi - \nu) \cdot \omega_{\phi}^2 \right] = -\sin(\nu) \cdot Q \\ m_P a_{XP} = G_P - S_P \end{array} \right. \quad (1)$$

where: $\varepsilon_{\phi}, \omega_{\phi}$ – angular acceleration and angular velocity of the jib, $\varepsilon_{\nu}, \omega_{\nu}$ – angular acceleration and angular velocity of the load Q , a_{BC}, v_{BC} – acceleration and velocity of the longitudinal motion of the load Q , a_{XP} – vertical acceleration of the counterweight, L_{OB} – length of the jib, $\kappa_{OE}, \kappa_{OF}, \kappa_{OS}$ – normalised with respect to L_{OB} distances: $\overline{OE}, \overline{OF}, \overline{OS}$.

The optimisation of mechanical structures such as that, which is required in order to minimise the operating dynamic forces and maximum energy uptake is categorised as a vibration isolation method, involving the reduction of the energy of the vibration source

For each problem involving the dynamic behaviour of investigated crane mechanisms, the specific optimisation task is formulated by defining the objective function:

- 1) slewing mechanism \rightarrow minimising the change of the payload level position – Δy , whilst the winch is immobile,
- 2) counter weight \rightarrow minimising the jib lifting work,
- 3) jib lifting mechanism \rightarrow minimum force in the rope winch jib.

2. Parametric optimisation of a slewing mechanism

The first step in the optimisation of mechanisms in a crane with a pivoting jib should involve the slewing mechanism. The optimisation procedure will determine the position of the peak pulley whilst the objective function is the minimisation (reduction) of the horizontal track error. The change of the slewing range is implemented by the slewing mechanism. It is vital that the slewing motion does not bring about a change to the payload level position.

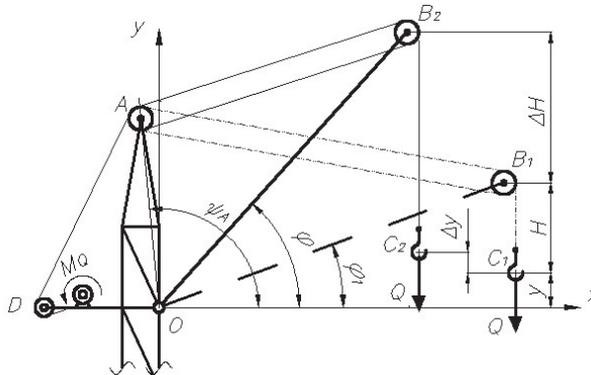


Fig. 2. Change of the jib's angular position in a one-link crane with a blocked winch

It is assumed that the hoisting load winch mechanism is blocked; thus, the rope length L from which the payload is suspended will not change during the hoisting phase.

In the case of extensible jibs, this condition can never be fully satisfied. The design of the slewing mechanism is considered satisfactory if the horizontal track error load during slewing – δ is less than 2%. The loads horizontal track error is understood as the absolute value of the ratio of the payload deviation from the straight-line trajectory to the total change of horizontal deviation:

$$\delta = \left| \frac{y(\phi_{\min}) - y(\phi_{\max})}{x(\phi_{\min}) - x(\phi_{\max})} \right| \cdot 100\% , \quad (2)$$

where: the angles ϕ_{\max} and ϕ_{\min} correspond to the lowest and the highest position of the jib, respectively.

Two configurations of the slewing mechanism represented by the jib's inclination angles ϕ_1, ϕ_2 are shown in Fig. 2. Thus, we write:

$$\begin{cases} i_w \cdot \overline{AB_1} + \overline{B_1C_1} = L \\ i_w \cdot \overline{AB_2} + \overline{B_2C_2} = L \\ L = const \end{cases} \quad (3)$$

The change of the jib's angular position involves a change of distance between the axes of the rope pulley B and the top pulley A , thus changing the length of the rope's free end section ΔL_{BC} on which the payload is suspended. On the other hand, when the pulley dimensions are omitted as negligibly small in relation to the distance between them, ΔL_{BC} can be derived from the formula:

$$\Delta L_{BC} = \Delta H - \Delta y = i_w (L_{AB1} - L_{AB2}) , \quad (4)$$

where: i_w – transmission ratio of the compensating pulley block, L_{ABi} – distance between the rope pulleys A and B for an arbitrary i -th position of the jib (ie $L_{ABi} = \overline{ABi}$).

Comparing two arbitrary angular positions of the jib, we get the formula expressing the payload height:

$$\begin{cases} y_1 = L_{OB} \cdot \sin(\phi_1) - H \\ y_2 = L_{OB} \cdot \sin(\phi_2) - H - (\Delta H - \Delta y) \end{cases} . \quad (5)$$

The change of the payload position level Δy caused by varying the jib's angular position $\phi_1 \rightarrow \phi_2$ is given as:

$$\Delta y(\phi) = L_{OB} \cdot \sin(\phi) - L_{OB} \cdot \sin(\phi_1) - i_w [L_{AB}(\phi_1) - L_{AB}(\phi)] , \quad (6)$$

$$\text{and: } L_{AB}(\phi) = \sqrt{L_{OA}^2 + L_{OB}^2 - 2L_{OA}L_{OB} \cdot \cos(\psi_A - \phi)} , \quad (7)$$

where: L_{OA} – distance between the rotation axis of the jib O and the top pulley A , ψ_A – angle of horizontal inclination of the line connecting the rotation axes of the jib O and the top pulley A (typically $\pi/3 \leq \psi_A \leq 2\pi/3$).

For a stabilised angular position of the jib ϕ_1 , we get:

$$\Delta y(\phi) = L_{OB} \left[\sin(\phi) - \sin(\phi_1) \right] - i_c \left[\sqrt{\kappa_{OA} + 1 - 2\kappa_{OA} \cos(\psi_A - \phi)} - \sqrt{\kappa_{OA} + 1 - 2\kappa_{OA} \cos(\psi_A - \phi_1)} \right] \quad (8)$$

where: $\kappa_{OA} = \frac{L_{OA}}{L_{OB}}$. (9)

In Fig. 1, the hook is attached directly to the end of the rope. In most cranes, an additional pulley block is connected between the jib top incorporating the pulley B and the hook, thus forming a sheave block with the transmission ratio $i_z > 1$. In this situation, the transmission ratio of the entire slewing mechanism becomes $i_c = i_w/i_z$, where $i_{c \min} = 3 [2, 3]$.

Thus, the formulated optimisation problem uses an objective function Δy , the decision variables being κ_{OA} and the angle ψ_A . The length L_{OB} and the transmission i_w (i_c) are taken as constant in the optimisation procedure. It is assumed that $L_{OB} = 30$ m, and the angle variability is in the range $\phi \in [15^\circ - 75^\circ]$.

Optimisation problem 1

The optimisation problem involves finding the optimal values of κ_{OA} and the angle ψ_A for which the quadratic functional $J(\kappa_{OA}, \psi_A)$ reaches its minimum, assuming that $\phi_1 = \phi_{\min}$.

$$J(\kappa_{OA}, \psi_A) = \int_{\phi_{\min}}^{\phi_{\max}} \left[\Delta y(\phi, \kappa_{OA}, \psi_A) \right]^2 d\phi. \quad (10)$$

The adopted criterion is important, yet still insufficient. One has to bear in mind that it is crucial that the derivative $dy/d\phi$ be minimised, since it determines the inertia forces acting upon the slewing mechanism during the hoisting or lowering the jib. With the weight R being ascribed to the function Δy , and the function $dy/d\phi$ added with its ascribed weight P , we get a new optimisation criterion which combines the two previous criteria [1].

$$J(\kappa_{OA}, \psi_A) = \int_{\phi_{\min}}^{\phi_{\max}} \left\{ P \cdot \left[\frac{dy(\phi, \kappa_{OA}, \psi_A)}{d\phi} \right]^2 + R \cdot \left[\Delta y(\phi, \kappa_{OA}, \psi_A) \right]^2 \right\} d\phi. \quad (11)$$

Restrictions imposed on the fixed jib length L_{OB} :

$$\left\{ \begin{array}{l} i_w \geq 3 \text{ where: } i_w = 2n+1, \text{ and } n=1,2,\dots, \\ \frac{\pi}{3} \leq \Psi_A \leq \frac{2\pi}{3}, \\ 0 \leq k_A \leq \frac{1}{2}. \end{array} \right. \quad (12)$$

When the functional (10) is replaced by (11) in the optimisation problem 1 for the stable conditions (12), we get new solutions for the parameters κ_{OA}, Ψ_A . It appears, that extending the optimisation criterion to incorporate the condition imposed upon the derivative $dy / d\varphi$ leads to the minimisation of the inertia force and further, reduces the deviation from the straight-line trajectory in the payload's motion in relation to solution (10) [1, 2, 3]. For two values of transmission of the compensating rope system: $i_w = 3$ and $i_w = 5$ for the fixed values of weight coefficients $P = 1$ and $R = 1$ in functional (12), we get:

$$i_w = 3 \rightarrow \left\{ \begin{array}{l} \kappa_{OA} = 0.3078 \\ \Psi_A = 83.2674^\circ \end{array} \right., \quad i_w = 5 \rightarrow \left\{ \begin{array}{l} \kappa_{OA} = 0.1901 \\ \Psi_A = 85.9712^\circ \end{array} \right. \quad (13)$$

The hook's trajectory deviation from the straight-line depends on the transmission ratio of lifting mechanism and becomes for $i_w = 3 \rightarrow \delta_3 = 1.242\%$, and for $i_w = 5 \rightarrow \delta = 0.666\%$.

Fig. 3 shows the trajectory of the hook when the crane radius changes over its entire range, for each pair of solutions (13). When the transmission ratio of the jib lifting mechanism is increased, the payload's horizontal trajectory better approximates the straight-line motion; however, the rope resistance due to winding is also increased.

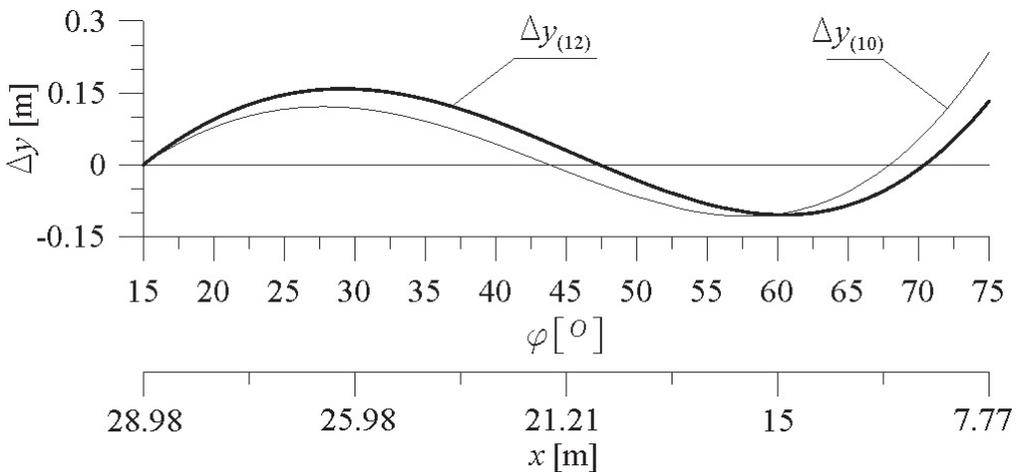


Fig. 3. Hook's trajectory during the radius change over its full range obtained for two criterions: (10) and (12)

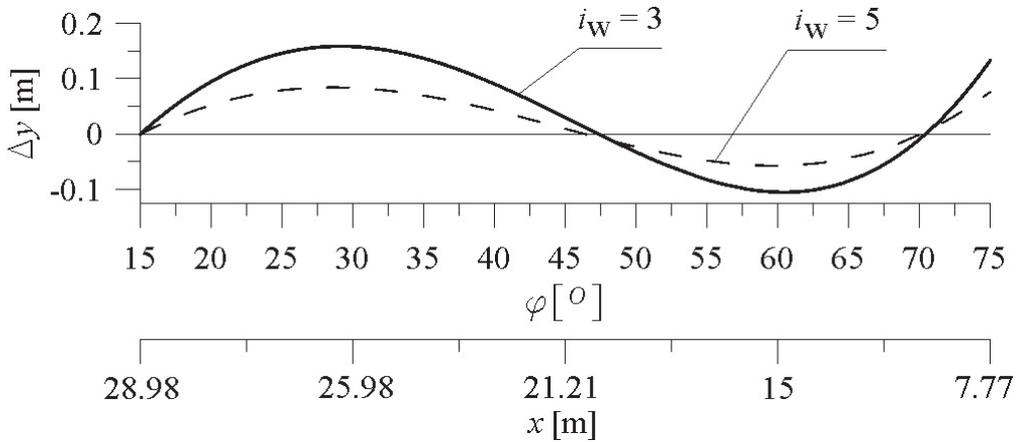


Fig. 4. Hook's trajectory during the radius change over its full range for two values of the transmission ratio of lifting mechanism $i_w = 3$ and $i_w = 5$

3. Parametric optimisation of the jib balance system

Balancing of the jib in a one-link crane requires the selection of the jib ballast weight and position of the pulley, with respect to the jib's rotation axis, in such a manner as to minimise the work required for slewing change. Figure 1 shows the loads acting on the jib in a one-link crane. Recalling the previous optimisation problem, the following designations are adopted: L_{OG} – distance between the rotation axis of the jib O and the pulley G , ψ_G – angle of horizontal inclination of the line segment \overline{OG} . The residual unbalanced moment of the jib is a function of the angular position ϕ :

$$M(\phi) = (G_w L_{OS} + QL_{OB}) \cos(\phi) - G_P L_{OF} \frac{L_{OG} \sin(\psi_G - \phi)}{L_{GF}(\phi)} - 3QL_{OB} \frac{L_{OA} \sin(\psi_A - \phi)}{L_{AB}(\phi)}. \quad (14)$$

$$\text{where: } L_{GF}(\phi) = \sqrt{L_{OF}^2 + L_{OG}^2 - 2L_{OF}L_{OG} \cdot \cos(\psi_G - \phi)}. \quad (15)$$

Optimisation problem 2

In this optimisation task, $M(\phi, L_{OG}, \psi_G, L_{OP}, G_P)$, becomes the objective function and the decision variables are: position of the pulley G defined by distance – L_{OG} and angle – ψ_G , distance from the axis of the pin jib – O to the point where the rope counterweight is attached to the arm of – L_{OP} , weight of counterweight – G_P . Distances: L_{OA} , L_{OB} , L_{OS} and weight Q and G_w are constant parameters in the optimisation procedure. For counterweight configurations as shown in Fig. 1, where the rope is connected to the jib creating a mechanism with unilateral bonds, the jib is balanced without the payload Q . The task consists of the determination of the optimal values: $L_{OG}, L_{OP}, \psi_G, G_P$ for which the quadratic functional $J(L_{OG}, L_{OP}, \psi_G, G_P)$, reaches a minimum.

$$J(L_{OG}, \psi_G, L_{OF}, G_P) = \int_{\phi_{\min}}^{\phi_{\max}} [M(\phi, L_{OG}, \psi_G, L_{OF}, G_P)]^2 d\phi. \quad (16)$$

$$\text{Assumed condition: } \left\{ \begin{array}{l} \psi_A, L_{OA}, L_{OB}, L_{OS}, G_W, Q (Q=0) - \text{known parameters,} \\ M(\phi, L_{OG}, \psi_G, L_{OF}, G_P) > 0 \text{ for each } \phi_{\min} \leq \phi \leq \phi_{\max}, \\ 0.5G_W \leq G_P \leq 1.7G_W \\ 0 < L_{OG} \leq \frac{1}{2}L_{OB} \\ 0 < L_{OF} \leq L_{OB} \\ \frac{\pi}{3} \leq \psi_G \leq \frac{2}{3}\pi \end{array} \right. \quad (17)$$

The solution to the optimisation task No. 2, for $G_w = 45 \text{ kN}$, $L_{OS} = 12.857 \text{ m}$, $L_{OA} = 9.234 \text{ m}$, $\psi_A = 83.2674^\circ$, is the set of parameter values such that the functional (16) is minimised for the imposed constraint conditions (18):

$$\left. \begin{array}{l} L_{OG} = 7.0605 \text{ m} \\ L_{OF} = 30 \text{ m} \\ \psi_G = 85.489^\circ \\ G_P = 67 \text{ kN} \end{array} \right\} \rightarrow L_\phi = \int_{\phi_{\min}}^{\phi_{\max}} M(\phi, L_{OG}, \psi_G, L_{OF}, G_P) d\phi = 51.43 \text{ kJ} \quad (18)$$

It appears that the best solution is obtained when the counterbalance rope is attached to the end of the jib, i.e. when $L_{OF} = L_{OB}$. Optimisation of the rope mechanism in the counterweight rope is discussed in more detail in [1] and the assumption that the counterbalance rope is attached to the tip of the jib is adopted based on a review of the existing crane design options. From the standpoint of mathematics, solution (18) confirms the validity of this assumption. Polar coordinates of the pulley mechanism in a counterweight are $-G [7.0605 \text{ m}, 85.489^\circ]$.

The effectiveness of the parametric optimisation of the movable counterweight mechanism is expressed as work $-L_\phi$ needed to change the jib's angular position over the entire variability range of its inclination angle.

Under conditions defined thus, this quantity is expressed as the integral (18) and equals 51.43 kJ. Finally, it is recommended that the counter jib ballast weight should be taken as 10% less than the value predicted in the optimisation problem to make up for resistance due to friction when the jib is lowered. This recommendation applies only to unilaterally constrained mechanisms. When a mechanism with bilateral constraints is considered, for example, a lever mechanism in a four-bar linkage, the positive residual torque requirement can be eliminated. The jib slewing work could be effectively reduced through optimising the structural design of such a mechanism.

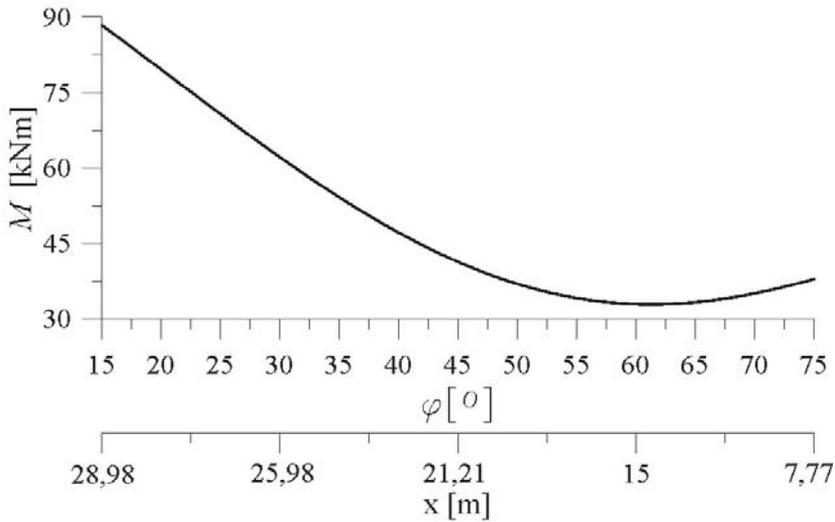


Fig. 5. Residual moment of jib unbalance as a function of the radius change

4. Parametric optimisation of the jib lifting mechanism

Optimisation of the slewing mechanism discussed in Section 1 could in fact be applied to the rope mechanism in a winch. The main objective was to ensure such roping configuration so as to minimise the horizontal hook trajectory error for the full variability range of the change in the jib's angle of horizontal inclination when the winch is blocked. Forces required to lift the jib have not been considered so far. Recalling (14), the force acting on the rope lifting the jib can be written as:

$$S_w(\phi) = \frac{L_{EW}(\phi)}{L_{OE}L_{OW}\sin(\psi_w - \phi)} M(\phi), \quad (19)$$

$$\text{where: } L_{EW}(\phi) = \sqrt{L_{OW}^2 + L_{OE}^2 - 2L_{OW}L_{OE} \cdot \cos(\psi_w - \phi)}. \quad (20)$$

Optimisation problem 3

The optimisation problem involving the jib lifting mechanism consists of finding the point where the rope is attached to the jib, as well as the polar coordinates of the pulley axes – $W [L_{OW}, \psi_w]$ associated with the tower crane, for which the force in the winch will be the lowest in terms of rms value and should be positive. All parameters determined in earlier sections remain constant throughout the optimisation of lifting the jib mechanism.

$$J(L_{OE}, L_{OW}, \psi_w) = \int_{\phi_{\min}}^{\phi_{\max}} [S_w(\phi, L_{OE}, L_{OW}, \psi_w)]^2 d\phi, \quad (21)$$

$$\text{Assumed condition: } \left\{ \begin{array}{l} \psi_A, \psi_G, L_{OA}, L_{OB}, L_{OS}, L_{OA}, L_{OB}, G_w, Q, G_p - \text{known parameters,} \\ S_W(\phi, L_{OE}, L_{OW}, \psi_W) > 0 \text{ for each } \phi_{\min} \leq \phi \leq \phi_{\max}, \\ 0 < L_{OE} \leq L_{OB} \\ 0 < L_{OW} \leq \frac{1}{3} L_{OB} \\ \frac{\pi}{3} \leq \psi_W \leq \pi \end{array} \right. \quad (22)$$

The solution to the optimisation task No. 3 for the nominal value of load $Q = 50$ kN is the following set of parameter values that minimise functional (21), under the imposed conditions (22):

$$\left. \begin{array}{l} L_{OE} = 30m \\ L_{OW} = 10m \\ \psi_W = 116.4911^\circ \end{array} \right\} \quad (23)$$

The best solution is obtained when the rope is attached to the end of the jib, that is when $L_{OE} = L_{OB}$. Polar coordinates of the pulley axes W [10 m, 116.4911°]. The torque required to hoist the jib expressed in terms of (14) is not dependent upon parameters of the jib lifting mechanism and neither is the work required to lift the jib.

For previously determined parameters of the slewing and counterweight mechanisms, and under the loading conditions due to the nominal payload – Q and the weight of the jib G_w operating at the distance – L_{OS} from the axis of the pin jib, the hoisting work becomes:

$$L_\phi = \int_{\phi_{\min}}^{\phi_{\max}} M(\phi) d\phi = 58.07 \text{ kJ} \quad (24)$$

Optimisation of the jib lifting mechanism results in the reduction and balancing of forces in the rope over the entire range of angle variability $\phi \in [15-75^\circ]$.

In Fig. 6, the forces are compared that act on the rope hooked on the movable end of the jib and which runs through a pulley located at the point A or G or W , depending on the design option, in accordance with designations shown in Fig. 1. Three plots of force acting on the jib winch rope are derived and their common feature is the minimum value achieved for the slewing angle – $\varphi \approx 50^\circ$. The least favourable force variability pattern is obtained when the axis of the pulley in the jib lifting mechanism coincides with that in the pulley of counterweight mechanism – G . The values of force acting in the rope – S_w decrease from 22.1 kN to nearly zero then rise again to achieve the maximum angle of deception, which is 84.0 kN (dashed line – G in Fig. 6). The variability pattern of the force acting on the rope was achieved when the axis of the pulley in the jib lifting mechanism coincides with that of the pulley in the winch mechanism – A . The force value S_w decreases from 16.85 kN to nearly zero and then rises again to 73.6 kN for a maximum value of angle φ , (thin line – A in fig. 6).

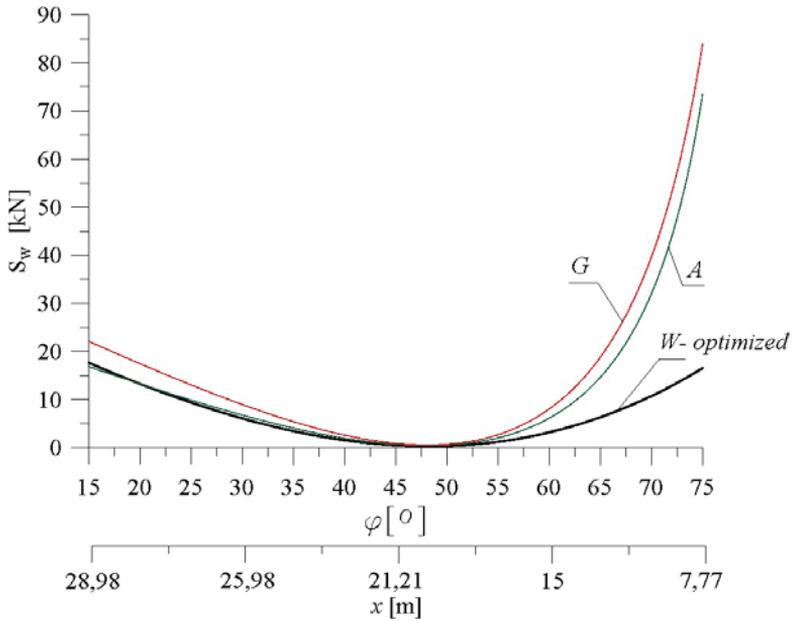


Fig. 6. Controlling forces acting in the rope through selection of the rotation axis of the pulley in the jib-lifting mechanism (plot designations correspond to points A, G, W in Fig. 1)

The most favourable pattern of force acting upon the rope is obtained when the axis of rotation of the pulley in the jib lifting mechanism is at point – W. The values of force S_w go down from 17.67 kN to nearly zero and then rises again to approaching 16.56 kN for the maximum value of the angle φ (thick line – W in Fig. 6).

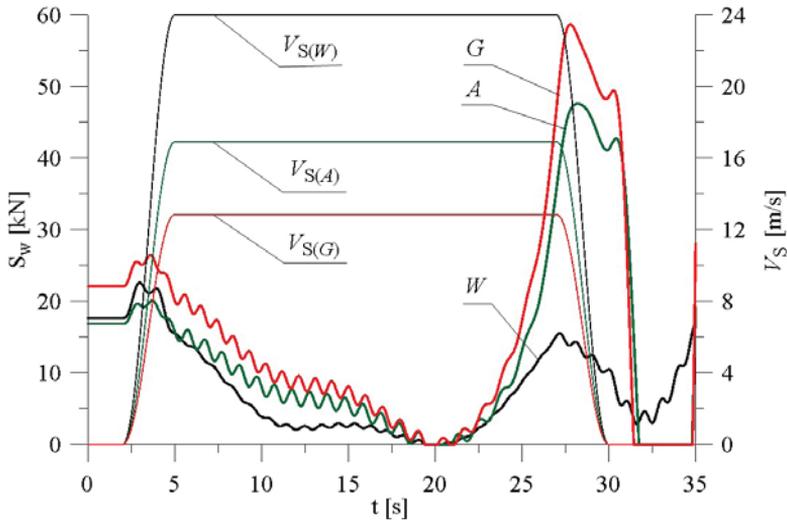


Fig. 7. Comparison of dynamic forces acting in the rope depending on the position of the pulley in the jib-lifting mechanism (plot designations correspond to points A, G, W in Fig. 1)

To verify the optimization results in dynamic conditions it is required that flexibility in the system, including rope flexibility, should be taken into account. Basing on the catalogue data, the universal model of kinematic excitations is adopted differing in the steady-state velocity values for specific mechanisms. The duty cycle of each mechanism involves the following stages: start, steady-state motion and braking, yielding a trapezoidal characteristics of drive velocity. Figure 7 confirms the optimization results under dynamic conditions.

Advantages of minimising the force acting on the rope in the jib lifting mechanism are:

- ▶ Small rope diameter → small pulley → low resistance during rope winding
- ▶ Low-power electric motors (approximately 7 kW) → reduced energy demand
- ▶ Small force variations in ropes → less overloading of electric motors → little overheating of engines

Because of the unilateral constraints in rope mechanisms, it is recommended in the optimisation process that the jib weight should be taken 10% less than in real life conditions.

5. Concluding remarks

Optimisation tasks involving the three-rope mechanisms in a one-link jib crane lead us to the following conclusions:

- 1) The application of dedicated software (such as Mathcad) to solve variational problems such as finding a minimum of properly formulated quadratic functionals proves to be a very effective and rapid solution to parametric optimisation problems.
- 2) Even though functionals (9), (10), (14), (19) are formally quadratic, it is not required that the Riccati equations be solved.
- 3) When the optimisation criterion for the slewing mechanism is extended to incorporate the condition imposed on the derivative $dy/d\varphi$, the form of the quadratic functional (9) becomes more complicated, but the numerical solution can still be found.
- 4) The optimisation effectiveness of the boom luffing mechanism determines the level of vibration reduction of the cargo hung on the hook.
- 5) The optimisation problem is solved and solutions are obtained in the form of a set of mechanism parameters for which the work involved in payload hoisting should be minimal. The force acting in line in the jib lifting mechanism should be minimal.
- 6) For the assumed lifting capacity and distance jaunt, we get a crane mechanism structure that guarantees the minimal energy consumption.

References

- [1] Chwastek S., *Optimisation of Crane Mechanisms – Selected Problems*, Key Engineering Materials, Vol. 542, Feb. 2013.
- [2] M. Scheffler M., Pajer G., Kurh F., *Fördertechnik. Unstetigförder, Krane-mechanische Ausführungen und Stahlwerke*, VEB Verlag Berlin 1975.
- [3] Piątkiewicz A., Sobolski R., *Dźwignice*, WNT, Warszawa 1977, Symbol 78620/Tw. (in Polish).
- [4] Abdel-Rahman, E.M., Nayfeh, A.H., and Masoud Z.N., *Dynamics and control of cranes: A review*. Journal of Vibration and Control, Vol. 9, No 7, 2003, 863–909.
- [5] Zrnić M., Gaši V. Bošnjak S. Đorđević M., *Moving Loads in Structural Dynamics of Cranes: Bridging the Gap Between Theoretical and Practical Researches*, FME Transactions, 292, VOL. 41, No 4. 2013.
- [6] Xue Y. Xue, Wang, W., Ji M.S., Wu N., *The Dimensionless-Parameter Robust Optimization Method Based on Geometric Approach of Pulley Block Compensation In Luffing Mechanism*. International Conference of Electrical, Automation and Mechanical Engineering (EAME 2015).
- [7] Dong Soo Kim, Jongsoo Lee, *Structural Design of a Level-Luffing Crane Through Trajectory Optimization and Strength-based Sized Optimization*. Structural and Multidisciplinary Optimization, Struct. Multidisc Optim., 2015, 515–531, DOI 10.1007/s00158-014-1139-2.

Sławomir Kowalski (skowalski@pwsz-ns.edu.pl)
The State Higher Vocational School in Nowy Sącz, Poland

THE INFLUENCE OF A CrN+a-C:H:W COATING ON THE DEVELOPMENT
OF FRETTING WEAR IN A MODEL OF A WHEEL–AXLE PRESS-FIT JOINT
ON A WHEEL SET OF A RAILWAY VEHICLE

WPLYW POWŁOKI CrN+a-C:H:W NA ROZWÓJ ZUŻYCIA
FRETINGOWEGO W MODELU POŁĄCZENIA WTŁACZANEGO
KOŁO–OŚ ZESTAWU KOŁOWEGO POJAZDÓW SZYNOWYCH

Abstract

The tests were conducted on a wheel/axle press-fit joint model, which consisted of a shaft and a sleeve. Macrographic observations were demonstrated fretting wear on the shaft surface with and without coatings. In the case of the uncoated shaft, wear around the entire circumference of the axle seat was visible in the form of a peculiar ring of a specific width. The coated shaft surface was distinguished by a considerably smaller number of visible traces of wear. Wear was observed around the entire circumference of the axle seat, was spaced at random, and insignificantly sized areas each time. Micrographic observations with the use of a scanning microscope demonstrated that fretting was primarily comprised of the build-up of the material from both surfaces joined together. In addition to the build-up, surface micro-abrasion, micropits and microcracks are observed, albeit to a lesser extent.

Keywords: PVD coating, CrN+a-C:H:W, rotational bending, fretting wear, press-fit joint, wheel set

Streszczenie

Badania wykonano na modelu połączenia wtłaczanego koło–oś, który składał się z wału i tulei. Przeprowadzone badania makrograficzne wykazały występowanie zużycia frettingowego na powierzchni wału bez powłok i z powłokami. W przypadku wału bez powłoki zużycie widoczne jest na całym obwodzie podpięcia w postaci charakterystycznego pierścienia o określonej szerokości. Powierzchnia wałów z powłoką charakteryzowała się znacznie mniejszą ilością widocznych śladów zużycia. Zużycie obserwowane jest na całym obwodzie podpięcia rozmieszczone jest losowo i za każdym razem zajmuje niewielkie powierzchnie. Badania mikrograficzne z użyciem mikroskopu skaningowego wykazały, że na zjawisko frettingu składają się przede wszystkim nalepy materiału pochodzące z obu łączonych powierzchni. Obserwuje się także mikrowytarcia powierzchni, mikrowżery i mikropęknięcia.

Słowa kluczowe: powłoka PVD, CrN+a-C:H:W, zginanie obrotowe, zużycie frettingowe, połączenie wciskowe, zestaw kołowy

1. Introduction

Wheel systems are among the most important railway vehicle assemblies. Their task is to run the vehicle on the track; thus, wheel systems should be distinguished by appropriate durability and reliability. History has revealed many examples which show that even minor damage to them can be the cause of vehicle derailing – this carries financial implications related to damage to infrastructure and, in extreme cases, it results in casualties.

Wheel sets, in particular the wheel/axle joint, are the main elements determining the reliability of wheel systems. Difficult wheel set operational conditions result from a complex load state – this is comprised of the vertical load depending on the rail vehicle weight, lateral forces acting on the joint of the wheel edge and rail head during passage through a curve, and dynamic forces coming into being as a result of the rolling of the wheel set on a rail. The loads mentioned above may cause the development of fatigue wear, to which the wheel/axle push-fit joint zone is most susceptible. Those loads are a natural phenomenon accompanying railway vehicle operation, in relation to which we are unable to eliminate them. Therefore, other solutions should be sought which will prolong the life of wheel sets.

Railway vehicles are equipped with various kinds of wheel sets whose structures depend upon many factors. However, special steel with exceptionally high strength parameters is used for the construction of any wheel set, regardless of its structural details. Moreover, each wheel set is also subject to close technical inspections governed by standards and other discipline-specific regulations. This notwithstanding, damage and premature wear occurs.

Fretting wear occurring at the wheel/axle joint is one type of damage resulting from wheel set operation. This wear is counted among tribological kinds of wear. The complexity of physical and chemical phenomena accompanying fretting wear is the reason why the unambiguous definition of that kind of wear has not yet been provided. It is only known that the occurrence of oscillatory tangential displacement between mating surfaces pressed against each other with an appropriately high force is the necessary condition for the initiation of fretting wear. According to many scientists, the oscillation amplitude needed to initiate wear is in the range of 25–150 μm .

Fretting is found in almost all fields of technology in which mating elements meet the conditions listed above – elements of airplanes [1], medical implants [2, 3], and elements of nuclear power plants [4, 5] may be mentioned here.

It transpires from literature available to the author that few scientists are involved in investigating fretting wear in press-fit joints. This is probably related to the joint disassembly issue. Inappropriate joint disassembly may cause damage to or the deformation of the resulting wear image. This kind of joint does, however, accumulate in it all the conditions conducive to the development of fretting wear. There is a specific pressure between the surfaces of the connected elements, and the relative displacement of those surfaces occurs.

Among the publications on fretting wear testing in press-fit joints, those under [6–8] may be mentioned. These are mainly tests enabling the recognition of wear images or publications concerned with the description of the fretting wear development mechanisms. The influence of various factors on fretting wear intensity was tested – these

factors included roughness parameters of the top layer and the assembly technology. There are still too few tests concerning the mitigation of the development of wear in press-fit joints. In his previous research, the author of this publication suggested the modification of the top layer through the use of strengthening treatment: surface hardening, nitriding and finish rolling. Test results demonstrated an insignificant influence of those processes on the mitigation of the development of wear. In the case of finish rolling, the shaft surface affected by wear is considerably larger than in the case of shafts without additional top layer treatment. This stemmed from the fact that the finish rolling process led to the 'smoothing' of the surface. Mating surfaces with low roughness parameters are susceptible to the creation of adhesive bonds – this is why other processes must be sought. These other processes should be more effective in the mitigation of fretting on the one hand, and not too costly on the other. It seems that the use of coatings applied by means of the PVD method are a good solution.

Many pieces of literature can be found in which authors demonstrate good anti-wear properties of this kind of coatings, especially low-friction coatings. The authors of [9] tested the properties of a-C:H:W coatings applied over a steel base surface. They proved that gradient coating systems lead to better coating efficiency in macroscopic and microscopic tests. The authors also proposed a new wear model which enables a changing stress field. The authors of [10] tested coatings applied to a graphite base surface; they demonstrated that multi-layer a-C:H:Zr and a-C:H:W coatings are very hard and non-porous. The authors of [11] tested the tribological characteristics of Cr/CrN/a-C:H:W/a-C:H coatings in lubrication conditions demonstrating that FM and GMO greases reduce friction and thus the wear of the coating and of the mating element surface. The author of [12] tested the influence of TiN and CrN intermediate layers on the tribological properties of type DLC coatings and in doing so proved that the properties of these coatings depend on their chemical composition. It became apparent during the comparison of a-C:H:W and CrN+ a-C:H:W coatings that it is the former which have better properties in nanoscale tribological tests and the latter which have better characteristics in microscale and macroscale tests. Tests have confirmed the improvement of DLC tribological properties with the use of intermediate layers. Tests conducted by the authors of [13] concerned the influence of hydrogen content on the tribological properties of type nc-WC/a-C:H coatings. These tests revealed that the coefficient of friction, the microstructure and the kind of bonds between carbon atoms greatly depend upon hydrogen content. In their tests, they demonstrated that the tested coatings might be used to improve the tribological properties of hard steels and hardened titanium alloys.

With consideration to knowledge based on literature, the analysis of CrN+a-C:H:W coatings was performed in this article with regard to the occurrence of fretting in press-fit joints.

In view of the dimensions of a wheel set and the related difficulties with the construction of a fretting wear test station, these tests were conducted on a wheel/axle press-fit joint model. The dimensional analysis made by the author of [14] shows that the results of model testing may be referred to real wheel sets.

2. The characteristics of the top layers of tested models

Tests were conducted on samples in two alternatives of the top layer finish of the shafts. In the first group, there were uncoated shafts which had top layers with a hardness of 160 HB. Shafts of the second test group were provided with a CrN+a-C:H:W coating, the properties of which are shown in Table 1.

Table 1. Properties of the CrN+a-C:H:W coating according to the manufacturer's data

| | |
|---|-------------|
| Coating material/coating structure | CrN+a-C:H:W |
| Micro hardness (HV 0.05) | 1000–1500 |
| Coefficient of friction (dry against steel) | 0.1–0.2 |
| Maximum service temperature (°C) | 300 |
| Coating temperature (°C) | < 250 |
| Colour | Anthracite |

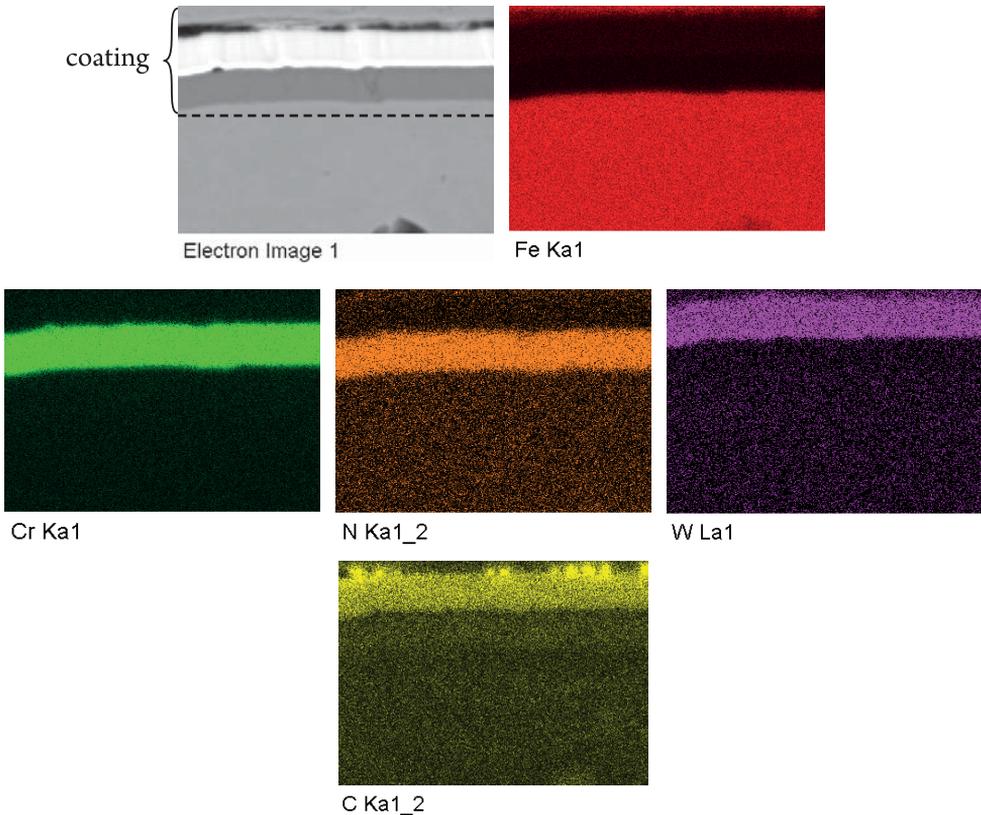


Fig. 1. Element distribution maps showing the chemical composition of the coating

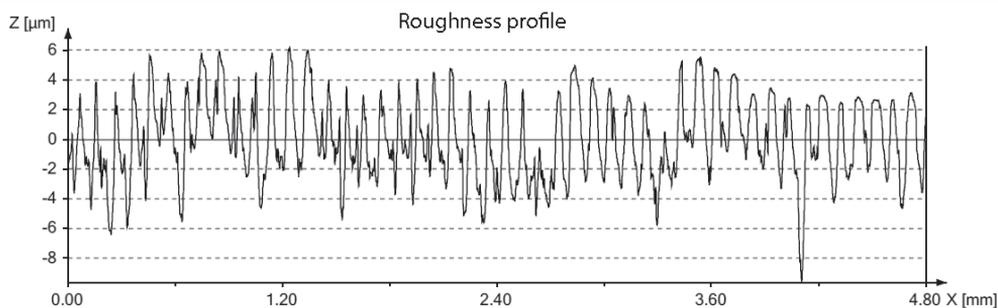
The coating was applied to the shafts by means of the reactive spraying method in a PVD process. The coating structure and chemical composition in the form of a chemical element distribution map is presented in Fig. 1. The coating consists of three layers and is colloquially called WC/C. The first layer is chromium nitride (CrN), the task of which is to improve coating adhesion to the surface of the steel base. The next layer is tungsten carbide (WC), which protects the surface of the base against abrasion and is responsible for the transfer of high pressures. The third layer, called the external layer, directly mates with the sleeve. According to literature, the atomic composition of this layer is as follows: 12% W, 70% C, 15% H, 3% Ni [15–16]. Nickel is an outcome of the coating generation process.

In the case of the tests of fretting wear in a press-fit joint, the appropriate hardness of the top layer and its roughness parameters prior to joint assembly play an important role. The roughness profile and selected parameters of the uncoated (a) and coated (b) top layer of the shaft are shown in Fig. 2.

The diagram showing shaft microhardness in the function of the distance from the surface is presented in Fig. 3.

a) uncoated shaft

| | | | | | |
|----|--------------------|----|---------------------|----------------------------|----------|
| Ra | 2.06 μm | Rz | 11.15 μm | Rmr(c=2.78 μm) | 18.062 % |
|----|--------------------|----|---------------------|----------------------------|----------|



b) coated shaft

| | | | | | |
|----|--------------------|----|---------------------|----------------------------|---------|
| Ra | 1.68 μm | Rz | 11.57 μm | Rmr(c=2.78 μm) | 1.300 % |
|----|--------------------|----|---------------------|----------------------------|---------|

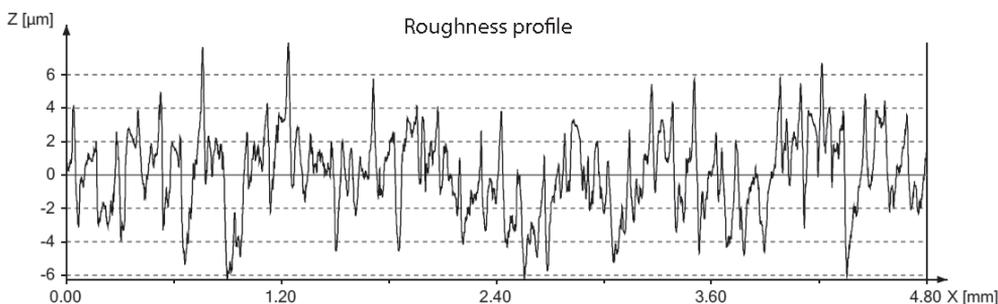


Fig. 2. Roughness profile of the shaft surface

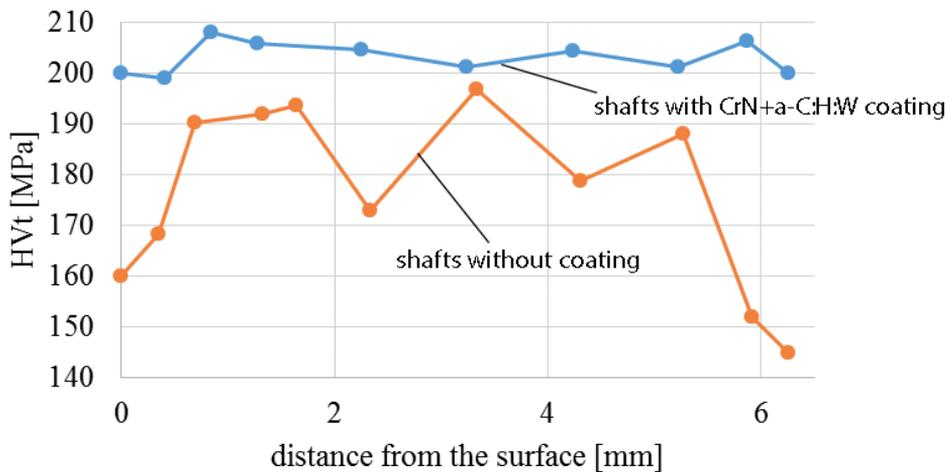


Fig. 3. Microhardness distribution

3. Test methodology

Wear tests were conducted on a model of a wheel/axle push fit joint of a railway vehicle wheel set. The model consists of a sleeve forced onto a shaft with 0.02 mm negative allowance.

Model elements were made of the same materials as those from which a wheel and axle of a wheel set are made. The sleeve was made of P58 steel, and the shaft was made of C45 steel.

The model was designed in such a manner that the dimensional similarity to the real wheel set is retained. Retained – this primarily concerned the shaft and sleeve connection zone. The shaft length and diameter were dependent upon the fatigue testing machine structure. The diagram of the sample with dimensions is presented in Fig. 4.

As mentioned previously, two model groups were used in the fatigue tests. The first group contained base samples in which the top layer of the shaft was not additionally improved. The samples of that group were used as a point of reference for the assessment of the top layer wear

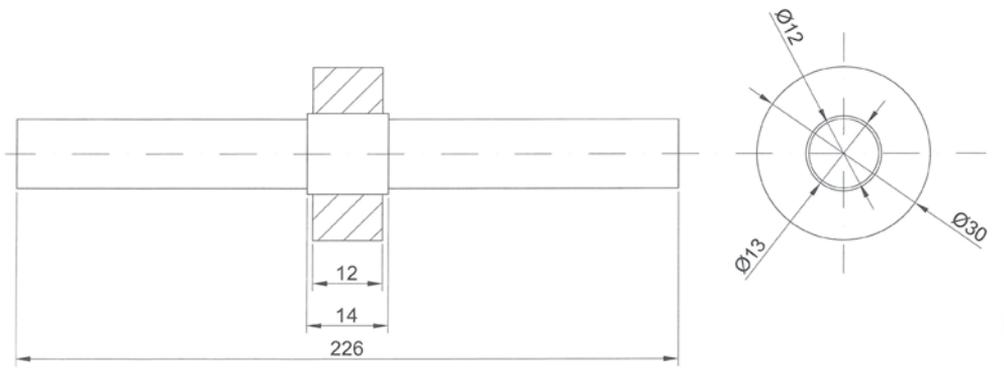


Fig. 4. Diagram of the test model with dimensions

intensity in the second group samples. In the second group of models, a Cr+a-C:H:W coating was applied to the top layer of the shaft.

In addition to an appropriate test model, the selection of a wear test station – which will, to the maximum extent, reflect the wheel set operational conditions described in the introduction – is an important issue. Primarily, the test station should enable the oscillatory tangential displacement of the mating surfaces. One such machines which meets the criteria is a MUJ fatigue testing machine, the structure of which is presented in Fig. 5.

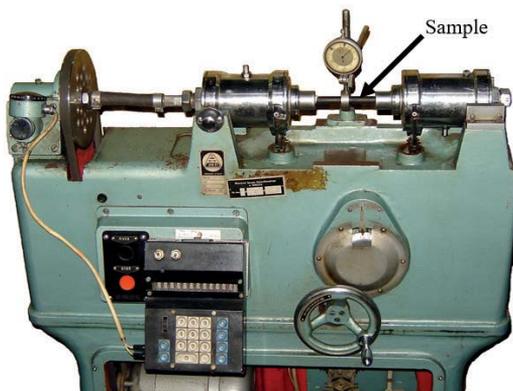


Fig. 5. The structure of a fatigue testing machine

The machine structure enables the generation of a periodically variable load with pure bending of a rotating model. Railway vehicle wheel sets rolling on a straight track (a situation when a railway vehicle does not move on a bend and hunting oscillation does not take place) are subjected to similar conditions. A situation in which a vehicle is on a bend was not covered in the tests.

The FEM analysis performed in the ANSYS software permitted the selection of the maximum value of a force which causes shaft deflection without leading to plastic deformation. The assumed 550 N force causes the maximum stresses to be reduced to 356 MPa (Fig. 6) and leads to maximum sample deflection, which is 0.52 mm. The most important parameters of wear tests are summarised in Table 2.

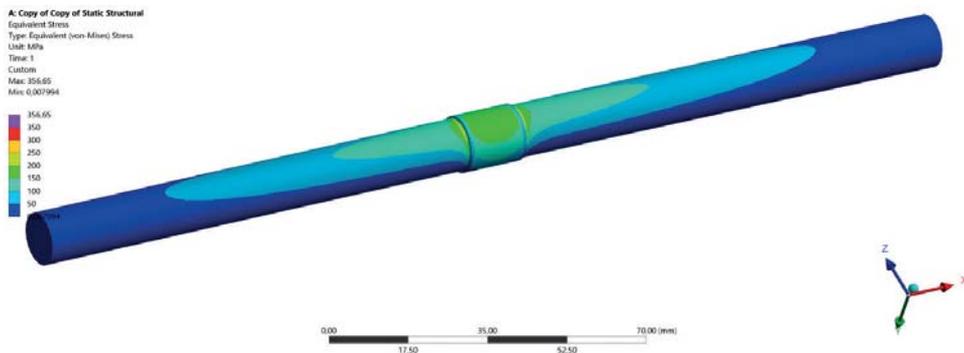


Fig. 6. Distribution of reduced stresses

Table 2. Summary of wear test parameters

| Parameter | Value obtained |
|--|--|
| maximum force necessary to force the sleeve onto the shaft | 4800 N (the uncoated shaft) |
| | 6600 N (the shaft with a Cr+a-C:H:W coating) |
| test model load | 550 N |
| normal stress | 118 MPa (for the 13 mm DIA shaft section) |
| | 93 MPa (for the 12 mm DIA shaft section) |
| number of cycles | 8×10^6 |
| number of revolutions | 1360 rpm |

After the wear tests were completed, the test model was cut in such a way that the arising wear image was not damaged. The joint was cut parallel to the shaft symmetry axis. As a result of this procedure, three samples for further testing and observation were obtained.

The observations and surveys of the shaft top layer aimed at determining its actual condition after wear tests and the influence of the tested coatings on fretting development and intensity. For this purpose, macrographic tests enabling the determination of the condition of the top surface of the shaft and fretting intensity were performed. Micrographic tests with the use of a scanning microscope provide an answer to the question as to which kinds of wear are comprised of fretting for the assumed wear test methodology. Analysis of the chemical composition by mean of the x-ray microanalysis in the EDS method enabled the determination of, among other things, the percentage share of elements in wear products.

4. Analysis of laboratory test results

Macrographic observations (Fig. 7) of the uncoated shaft surface confirm the test results obtained by the authors of [6, 17, 18], which show that fretting occurs at joint edges in the case of press-fit joints.

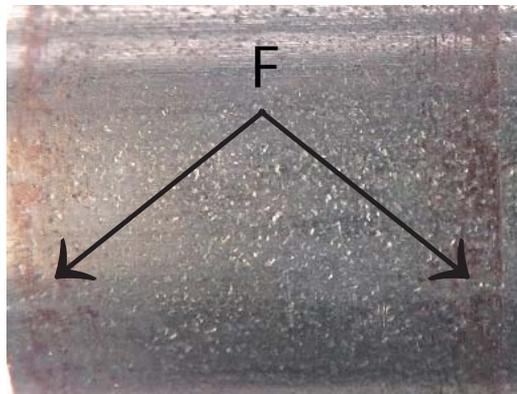


Fig. 7. The macrographic image of the shaft surface, F – fretting wear

In the case under analysis, fretting wear occurs around the entire circumference of the shaft axle seat. The width of the ring affected by wear reaches 2-3 mm and is the same on each side of the axle seat. Wear occurs at a distance of 2-5 mm from the axle seat edges. The tests of the topography of the top layer at the place of fretting wear indicates a considerable increase of the roughness parameters. The probable cause of the roughness increase is the wear products.

Microscopic observations with the use of an SEM confirm that the responsibility for the increase of roughness parameters rests to a large extent with material build-up at the shaft surface in the fretting wear zone visible in Fig. 8. Further observations show occasional occurrences of microcracks and micro-abrasion.

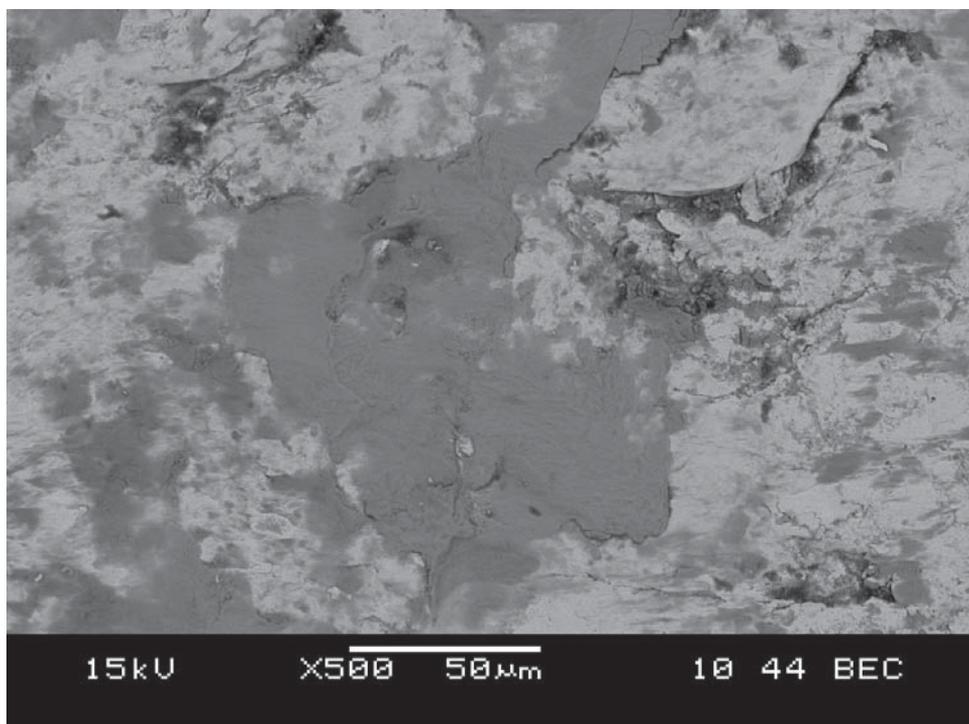
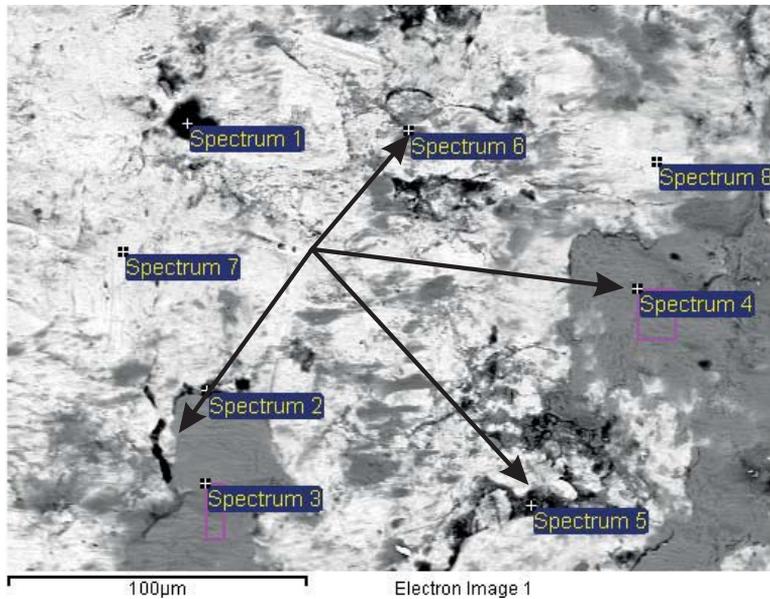


Fig. 8. The SEM image of the shaft surface in the fretting wear zone

The deformations of the top layer of the elements being connected result from the joint assembly process. The magnitude of these deformations depends upon the top layer's parameters such as roughness and hardness. These deformations cause the surface contact over the length of the joint to be heterogeneous. In the case under analysis, the mating surfaces have similar input parameters. The tangential force occurring in this case causes the mutual shearing of microprojections on both surfaces, thus creating wear products in the form of fine particles of the material, which will subsequently form material build-up at the top layer.



| Spectrum | Fe | O | C | Na | Si | S | Cl | K | Ca | Mn | Total |
|------------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-------|
| Spectrum 1 | 21.8 | 13.2 | 59.2 | 1.3 | 0.8 | 0.9 | 1.2 | 0.6 | 1.0 | - | 100.0 |
| Spectrum 2 | 51.4 | 16.7 | 26.4 | 1.4 | 1.3 | 0.5 | 0.8 | 0.5 | 0.5 | 0.4 | 100.0 |
| Spectrum 3 | 64.4 | 34.8 | - | - | 0.3 | - | - | - | - | 0.5 | 100.0 |
| Spectrum 4 | 60.7 | 38.5 | - | - | 0.4 | - | - | - | - | 0.4 | 100.0 |
| Spectrum 5 | 56.2 | 27.7 | 14.7 | - | 0.3 | - | - | 0.2 | 0.4 | 0.5 | 100.0 |
| Spectrum 6 | 61.9 | 31.6 | 3.7 | - | 1.7 | - | - | 0.5 | - | 0.5 | 100.0 |
| Spectrum 7 | 99.3 | - | - | - | - | - | - | - | - | 0.7 | 100.0 |
| Spectrum 8 | 99.4 | - | - | - | - | - | - | - | - | 0.6 | 100.0 |

All results in weight%

Fig. 9. EDS analysis of the elements at the shaft surface in the fretting wear zone

A peculiar feature of fretting damage is the brown colour typical of steel corrosion. This follows from the fact that wear products damage that has come into being as a result of adhesive bonds and, subsequently, plastic deformation, are susceptible to oxidation. This fact is confirmed by the EDS analysis of the chemical composition of wear products in the place of fretting wear. In Fig. 9, places marked with arrows show fretting damage in the form of material build-up. These places have an oxygen content from 27% to 40%; therefore, iron oxides come into being. The remaining measured places also contain oxygen, but its concentration is considerably lower.

Macroscopic observations of the coated top layer of the shaft after wear tests demonstrated fretting wear traces (the 'F' in Fig. 10). As in the previous case, these are located by both joint edges. The first traces appear 2 mm from the edge. Wear affects is randomly located at the axle seat circumference. The smallest surface area affected by wear is 0.5 mm², and the largest is approximately 14 mm². The width of the 'strip' affected by wear is different on each side.

Fretting comprises, to a large extent, material build-up most probably originating from the tearing off of the sleeve top layer micro-irregularities (Fig. 11). The inferior properties of the sleeve hub top layer in relation to the coated shaft axle seat cause precisely the sleeve hub surface to be susceptible to damage during joint assembly.

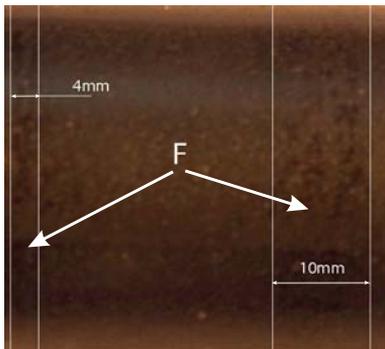


Fig. 10. The surface of a shaft with a CrN+a-C:H:W coating after wear tests

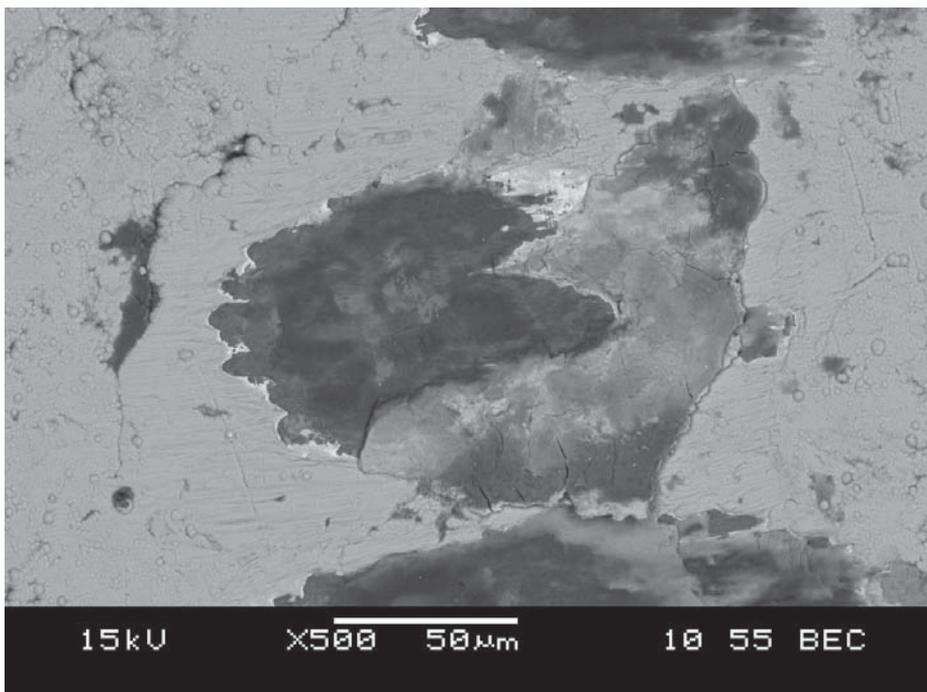
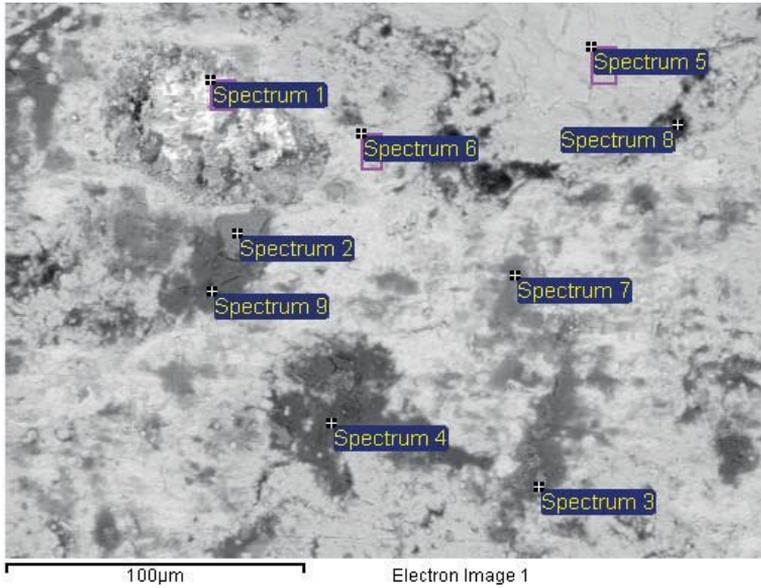


Fig. 11. Fretting in the form of material build-up on the coated shaft surface

This assumption is confirmed by the analysis of the elements occurring on the shaft surface in the fretting wear zone. The results of the analysis of the chemical composition at selected points of the shaft surface within the fretting zone are presented in Fig. 12.



| Spectrum | Elements related to the coating and sleeve structure | | | | | Elements related to the process of sample preparation for laboratory tests | | | | Total |
|------------|--|------|------|------|------|--|-----|-----|-----|-------|
| | Fe | O | C | W | Cr | Si | Ca | Mn | Ni | |
| Spectrum 1 | 7.1 | 5.4 | 19.4 | 53.7 | 10.6 | | – | | 3.8 | 100.0 |
| Spectrum 2 | 94.6 | – | 3.4 | – | 0.9 | 0.4 | – | 0.7 | – | 100.0 |
| Spectrum 3 | 93.8 | – | 4.1 | – | 1.0 | 0.4 | – | 0.7 | – | 100.0 |
| Spectrum 4 | 41.2 | 26.5 | – | 29.5 | 1.0 | – | – | – | 1.7 | 100.0 |
| Spectrum 5 | 0.6 | 1.0 | 26.1 | 66.8 | 0.9 | – | – | – | 4.6 | 100.0 |
| Spectrum 6 | 3.1 | 20.1 | – | 71.0 | 1.0 | – | – | – | 4.8 | 100.0 |
| Spectrum 7 | 40.3 | 29.1 | 6.2 | 21.9 | 1.3 | – | – | – | 1.2 | 100.0 |
| Spectrum 8 | 15.0 | 15.1 | 48.6 | 17.7 | 2.6 | – | 0.4 | – | 0.5 | 100.0 |
| Spectrum 9 | 42.4 | 26.1 | – | 28.5 | 1.0 | – | 0.5 | – | 1.6 | 100.0 |

All results in weight%

Fig. 12. EDS analysis of the elements on the shaft surface in the fretting wear zone

During the analysis of the chemical composition for a selected area affected by wear, macroscopic observations have demonstrated that wear is random in nature and is not continuous. This is proved by the chemical composition at the survey points 'Spectrum 1' and 'Spectrum 5'. It is mainly the elements related to the coating structure (carbon and tungsten) that occur there. In the case of the 'Spectrum 1' survey point, a small amount of chromium is also observed. This is caused by the micro-abrasion of the working part of the coating, which led to the uncovering of the first coating layer containing chromium. The total destruction of the coating did not, however, take place. Iron occurring at that point probably originates from the sleeve hub. Nickel occurring in that part is an effect of the manufacturing process of the coating.

The survey points 'Spectrum 2' and 'Spectrum 3' are the proof of the shearing of the micro-irregularities on the top layer of the sleeve hub during joint assembly. During forcing, torn-off micro-irregularities creating the so-called 'third body' were moving along the joint and filling the natural microcavities in the coating. Hence, the chemical composition in these places is primarily iron. These wear products did not undergo plastic deformation and were not oxidised. They did not take part in the rise of fretting, either.

The remaining survey points demonstrate the occurrence of fretting wear. In the case of the 'Spectrum 6' survey point, material build-up mainly consisting of tungsten is observed. This is evidence of the tearing off of micro-irregularities of coating as a result of adhesion, and of the creation of build-up which underwent plastic deformation during the latter part of assembly or operation. This deformed build-up was oxidised, hence the analysis of the chemical composition also showing the occurrence of oxygen. The 'Spectrum 8' survey point also signifies damage to the coating. Material build-up at this point is composed of carbon and tungsten (i.e. elements related to the coating structure) and of a small amount of iron. This build-up also underwent plastic deformation and, at a further stage, oxidation.

Wear products see above note analysed at the 'Spectrum 4', 'Spectrum 7' and 'Spectrum 9' survey points are the material build-up in which chemical composition is a mixture of elements originating from the top layer of the sleeve hub and of the coating. However, the occurrence of iron is noted in the vast majority of cases – this means that mainly the sleeve top layer was damaged. During operation, this build-up gradually underwent plastic deformation and oxidation. The analysis of the chemical composition in these survey points showed the presence of the same or similar amount of oxygen to that of tungsten. The presence of carbon is not noted.

Trace amounts of chromium observed in the 'Spectrum 2' to 'Spectrum 9' survey points originate from the local microdamage of the working part of the coating. The remaining chemical elements – such as silicon, calcium, manganese and nickel – are the result of the surface preparation for laboratory tests or the outcome of the coating production process.

5. Conclusion

The aim of this article was to present the results of tests of fretting wear in a press-fit joint and an assessment of the possibilities of using a CrN+a-C:H:W coating to reduce such wear.

The tests demonstrated that in the case of a joint in which the shaft top layer was not covered with the relevant coating, fretting wear occurs around the entire circumference in the form of a ring, the width and distance of which from the joint edge are different at each side. Fretting wear, of considerably lower intensity, however, was also observed on the surface of the coated shafts. Fretting wear occurred over the entire circumference, covered small areas of various shapes, and was spaced at random.

Test results confirmed the tests conducted by other authors specifically that input parameters of the top layer of the elements being connected have significant influence on the development of fretting wear. Appropriate roughness and hardness parameters reduce wear intensity. Tested coatings have, indeed, slightly lower roughness parameters in comparison with the uncoated shaft, but increasing top layer hardness by 25% proved sufficient for the reduction of adhesion and also of fretting wear.

Fretting in press-fit joints is a complex phenomenon. Irrespective of the kind of top layer, material build-up is the dominant kind of wear comprised of fretting. In addition to the build-up, but to a lesser extent, microcracks, micro-abrasion and abrasive wear are observed. The main factor responsible for these kinds of wear in press-fit joints is adhesion.

Study sponsored by grant no PB.S01-1/2017 obtained from State Higher Vocational School in Nowy Sącz

References

- [1] Bok-Won Lee, Jungjun Suh, Hongchul Lee, Tae-gu Kim, *Investigations on fretting fatigue in aircraft engine compressor blade*, Engineering Failure Analysis, Vol. 18, Issue 7, 2011, 1900–1908.
- [2] Sivakumar B., Chandra Pathak L., Singh R., *Role of surface roughness on corrosion and fretting corrosion behaviour of commercially pure titanium in Ringer's solution for bio-implant application*, Applied Surface Science, 401, 2017, 385–398.
- [3] Royhman D., Patel M., Runa M.J., Jacobs J.J., Hallab N.J., Wimmer M.A., Mathew M.T., *Fretting-corrosion in hip implant modular junctions: New experimental set-up and initial outcome*, Tribology International, 91, 2015, 235–245.
- [4] Fei Xue, Zhao-Xi Wang, Wen-Sheng Zhao, Xiao-Liang Zhang, Bao-Ping Qu, Liu Wei, *Fretting fatigue crack analysis of the turbine blade from nuclear power plant*, Engineering Failure Analysis, 44, 2014, 299–305.
- [5] Helmi Attia M., *Fretting fatigue and wear damage of structural components in nuclear power stations—Fitness for service and life management perspective*, Tribology International, Vol. 39, Issue 10, 2006, 1294–1304.

- [6] Zhang Y., Lu L., Gong Y., Zhang J., Zeng D., *Fretting wear-induced evolution of surface damage in press-fitted shaft*, *Wear*, 384–385, 2017, 131–141.
- [7] Song C., Shen M.X., Lin X.F., Liu D.W., Zhu M.H., *An investigation on rotatory bending fretting fatigue damage of railway axles*, *Fatigue Fract Engng Mater Struct*, 37, 2014, 72–84.
- [8] Guzowski S., *Analysis of fretting wear in clamped joints on example of rail vehicle wheelset axles*. Monograph 284, Krakow: Cracow University of Technology Press, 2003.
- [9] Gies A., Chudoba T., Schwarzer N., Becker J., *Influence of the coating structure of a-C:H:W coatings on their wear-performance: A theoretical approach and its practical confirmation*, *Surface and Coatings Technology*, 237, 2013, 299–304.
- [10] Richert M., Zawadzka P., Mazurkiewicz A., Smolik J., Leszczyńska-Madej B., Nejman I., Pałka P., Pietrzyk S., *Deposition of W/a-C:H:Zr and W/a-C:H:W multilayer coatings on substrate made of porous graphite by arc – Electron beam hybrid method*, *Surface and Coatings Technology*, 300, 2016, 19–24.
- [11] Dong-Wook Kim, Kyung-Woong Kim, *Tribological characteristics of Cr/CrN/a-C:H:W/a-C:H coating under boundary lubrication conditions with glycerol mono-oleate (GMO) and molybdenum dithiocarbamate (MoDTC)*, *Wear*, 342–343, 2015, 107–116
- [12] Madej M., *The effect of TiN and CrN interlayers on the tribological behavior of DLC coatings*, *Wear*, 317 Issue 1–2, 2014, 179–187.
- [13] Makowka M., Pawlak W., Konarski P., Wendler B., *Hydrogen content influence on tribological properties of nc-WC/a-C:H coatings*, *Diamond and Related Materials*, 67, 2016, 16–25.
- [14] Furmanik K., *Possibilities of dimensional analysis implementation in the investigations of belt inclination resistance on conveyor drums*, *Mining Science – Fundamental Problems of Conveyor Transport*, 21(2), 2014.
- [15] Michalczewski R., Piekoszewski W., Szczerek M., Tuszyński W., *The rolling contact fatigue of WC/C coated gears*, *Tribology* 4, 2011, 191–202.
- [16] Mercer C., Evans A.G., Yao N., Allameh S., Cooper C.V., *Material removal on lubricated steel gears with W- DLC-coated surfaces*, *Surface and Coatings Technology*, Vol. 173, Issue 2–3, 2003, 122–129.
- [17] Song C., Shen M.X., Lin X.F., Liu D.W., Zhu M.H., *An investigation on rotatory bending fretting fatigue damage of railway axles*, *Fatigue Fract Engng Mater Struct*, 34, 2014, 72–84.
- [18] Guzowski S., *Fretting wear expansion in clamped joints*, *Tribology* 4, 1994, 504–512.

Pawel Lempa (plempa@ialab.cs.kitami-it.ac.jp)

Michal Ptaszynski

Fumito Masui

Department of Computer Science Kitami Institute of Technology, Japan

THE USE OF GENETIC ALGORITHM TO OPTIMIZE QUANTITATIVE LEARNER'S MOTIVATION MODEL

WYKORZYSTANIE ALGORYTMU GENETYCZNEGO DO OPTIMALIZACJI ILOŚCIOWEGO MODELU MOTYWACJI UCZNIĄ

Abstract

The paper presents a method of optimizing Quantitative Learner's Motivation Model with the use of genetic algorithm. It is focused on optimizing the formula for prediction of learning motivation by means of different weights for three values: interest, usefulness in the future and satisfaction. For the purpose of this optimization, we developed a C++ library that implements a genetic algorithm and an application in C# which uses that library with data acquired from questionnaires enquiring about those three elements. The results of the experiment showed improvement in the estimation of student's learning motivation.

Keywords: optimization, genetic algorithm, Quantitative Learner's Motivation Model

Streszczenie

W artykule przedstawiono metodę optymalizacji ilościowego modelu motywacji ucznia z wykorzystaniem algorytmu genetycznego. Przedstawiona metoda polega na optymalizacji formuły przewidywania motywacji do nauki poprzez wykorzystanie różnych wag dla trzech różnych wartości: zainteresowanie przedmiotem, jego przydatność w przyszłości i zadowolenie z udziału w zajęciach. Na potrzebę optymalizacji stworzono bibliotekę C++, która implementuje algorytm genetyczny oraz aplikację w C#, która wykorzystuje tę bibliotekę razem z zebranymi danymi z ankiet w celu indukcji powyższych trzech elementów. Wyniki eksperymentu wykazały poprawę w szacowaniu motywacji uczniów.

Słowa kluczowe: optymalizacja, algorytm genetyczny, ilościowy model motywacji ucznia

1. Introduction

A genetic algorithm (GA) is an algorithm which looks for the best solution using heuristic searching based on natural selection of chromosomes known in genetics [10]. This approach has proven its utility in many cases, as it sometimes replaced other tools used in artificial intelligence, and was also often applied together with them to resolve a given research problem.

Quantitative Lerner's Motivation Model (QLMM) is a composition of three elements, which represent the attitude of students towards the attended courses. Quantification of those elements represents the general level of learning motivation. The three elements called interest, usefulness in the future, and satisfaction in original model have the same level of importance. However, experience shows that they are not equally important. Therefore, in this research we decided to perform an optimization experiment to find the best weights for these three elements.

For the experiment, we used two pieces of software. The first was the one used in Nobuta et al. [1], made for calculation of QLMM, which we modified by adding settable values of the weights for interest, usefulness, and satisfaction. The second software used our own library of Genetic Algorithm to find the best weights for the three values applied in QLMM.

For the optimization purpose, we used four types of genetic algorithms. The simple genetic algorithm, GA with limited lifetime of chromosomes, GA with sexual selection in reproduction and algorithm with both limited lifetime and sexual selection.

2. Related Research

There has been a number of research on applying Genetic Algorithm (GA) in various optimization tasks.

In language generation, an example of GA use was presented in the paper by Montero and Araki (2007) [3], where they described a method based on a random selection of a small number of phrases from a database, in which the genetic algorithm generated and evaluated trivial dialogue phrases. Another example is a creation of sophisticated texts like poetry described in [4] and in [5], where a genetic algorithm was used to find a solution that satisfies the constraints of grammaticality and meaningfulness or a story generator [7], where GA was used in a story planer to find space of possible stories because it greatly reduced the risk of getting stuck in the local optima.

In dialogue systems, an example of using Genetic Algorithm with Sexual selection was used by Araki and Kuroda (2006) [6]. Due to the use of this type of GA, a system in its initial state could be trained to sufficient level without any prior language information, like vocabulary or grammar.

3. Quantitative Learner's Motivation Model

Quantitative Lerner's Motivation Model (QLMM) [1] is composed of three elements representing the attitude of students towards the attended courses. Quantification of those elements represents the general level of learning motivation. These three elements are as

follows: interest, usefulness in the future and satisfaction. Each element corresponds to the points of view included in the ARCS model [14, 15].

A detailed description of the three basic elements of the model is presented below:

- ▶ Interest - contains elements reflecting the generally perceived interest and attention paid by the learners to the contents of the course and corresponds to “attention” in the ARCS model,
- ▶ Usefulness in the future - represents the potential to contribute to the improvement of the skills and knowledge possessed by the learners themselves and corresponds to “relevance” in the ARCS model,
- ▶ Satisfaction - contains the elements reflecting the expectations toward the class at the beginning of the course or the satisfaction of the course at the end of the school year and corresponds to “satisfaction” in the ARCS model.

4. Genetic Algorithm

To perform the optimization, a Simple Genetic Algorithm (SGA) was used at first [8]. In this algorithm, the chromosomes ($v(t)$) were used in the floating-point form, with a crossover:

$$\begin{aligned} v_1(t) &= v_1(t-1) a_1 + (1-a_1) v_2(t-1) \\ v_2(t) &= v_2(t-1) a_2 + (1-a_2) v_1(t-1) \end{aligned}$$

where:

a_1, a_2 - random numbers in the range [0..1], and the mutation is in the form:

$$v(t) = av(t-1)$$

For the selection of the size of the population, a solution has been proposed [9] in which the number of chromosomes of the population is a variable depending on the value of the evaluation function of entire population. This helps to avoid the situation in which too small population of solutions could lead to a convergence to the local optimum, and too high population to a significant increase in the calculation time. It is also assumed that, at different stages of evolution, the optimal number of population may be different. Because this parameter of chromosome age has been inserted, which is an integer in the range [0..max age], where max age is the maximum age of a chromosome and after exceeding it, chromosome will not be taken into account in further calculations. After each iteration of the algorithm, the age is increased by 1, while during the selection - chromosomes with higher age than the maximum are rejected. In this situation, there is no need to define the selection algorithm because the age of a chromosome is determined by the objective function. The age of a chromosome determines which chromosomes will take part in the creation of new solutions. In the calculation of the lifetime of a chromosome, a linear assignment was used in the following form:

$$MinLT + (MaxLT - MinLT) \frac{eval(v_i(t)) - AbsFitMin}{AbsFitMax - AbsFitMin}$$

where:

$MinLT$ – minimum possible age of a chromosome,

$MaxLT$ – maximum possible age of a chromosome,

$eval(v_i)$ – value of the adaptation function of a chromosome,

$AbsFitMin$ – the lowest value of the adaptation function found during all previous iterations,

$AbsFitMax$ – the largest value of the adaptation function found during all previous iterations.

5. Experiment

The data used for the experiments was collected from questionnaires for nine different courses for undergraduate students of 1st to 3rd year in the Kitami Institute of Technology. There were 5,040 answers collected at the beginning and at the end of the school year. Range values for the three elements of QLMM were from 1 to 5.

For the experiment, we used two pieces of software. The first one, written in C#, was developed previously for the quantification of learner's motivation [1]. The only change was made for adding settable values of weights for the three values of QLMM. The second software, written in C#, used our own library of Genetic Algorithm made in C++ [11]. The function of the second software was finding the best weights for QLMM. The diagram of the solution is showed in Fig. 1.

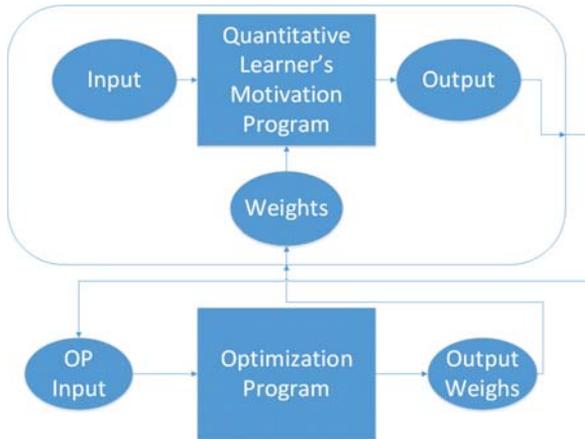


Fig. 1. Diagram of the solution

Solution steps:

- 1) Uploading data from excel files containing questionnaire answers to a program
- 2) Calculating QLMM in the first program without any weights for interest, usefulness in the future and satisfaction
- 3) Uploading results from the first program to the second
- 4) Calculating weights for the three elements of QLMM with the use of genetic algorithm
- 5) Calculating QLMM again in the first program with weights received from the second program
- 6) Uploading results from the first to the second program again

7) Repeating steps 4 to 6 until the end of all generations of used GA

We used four different types of genetic algorithms for optimization. The basic one was a simple genetic algorithm (SGA). The second algorithm used the limited lifetime of chromosomes. The third one was SGA with sexual selection in reproduction [12]. The last algorithm used both solutions used in the second and third type of GA. All of them had the same starting parameters.

- ▶ The type of representation: floating point,
- ▶ Crossover: 2-point, with a probability: 0:9,
- ▶ The probability of mutation: 0:1,
- ▶ The size of population: 100,
- ▶ The number of algorithm iterations: 2000.

All the results were compared to the output from basic program without optimization of the weights. All four solutions showed improvement in relation to original results. In Table 1, we showed the percentage values of improvement of precision and recall.

Table 1. Improvement in results after optimization with GA

| Genetic algorithm type | Improvement in Precision | Improvement in Recall |
|---|--------------------------|-----------------------|
| Simple Genetic Algorithm (SGA) | 6% | 7% |
| GA with limited lifetime | 13% | 15% |
| GA with sexual selection | 11% | 11% |
| GA with limited lifetime and sexual selection | 17% | 21% |

6. Conclusions

The paper presented a method of optimizing Quantitative Learner's Motivation Model with the use of different types of a genetic algorithm. For the experiments, we used data collected from questionnaires for undergraduate students. In the experiments, the program based on the research of QLMM used weights calculated in a separate program which used different types of a genetic algorithm to find optimal weights for interest, usefulness and satisfaction from QLMM. All the four solutions resulted in improvements of precision and recall used for the calculation of optimization of motivation model. The best solution was reached by means of the genetic algorithm with sexual selection in reproduction of chromosomes and their limited lifetime. The way of using a program allows for reusing it after a proper adjustment in other research for optimization of, e.g., binary classifiers [13]. In future, we are planning to use this solution in the optimization of sentiment analysis, fake reviews detection, cyberbullying detection and others from the natural language processing field.

References

- [1] Nobuta Y., Masui F., Ptaszynski M., *Modeling Learning Motivation of Students Based on Analysis of Class Evaluation Questionnaire*, Technical Transactions, 2-M/2015, 193–201.
- [2] Ekbal, A., Saha, S., *Simultaneous feature and parameter selection using multiobjective optimization: application to named entity recognition* International Journal of Machine Learning and Cybernetics, Volume 7, Issue 4, 2016, 597–611.
- [3] Calkin S. Montereio, Araki K., *Unsupervised language independent genetic algorithm approach to trivial dialogue phrase generation and evaluation*. Lecture Notes in Computer Science, Springer, Berlin, Heidelberg, Vol. 4592, 2007, 388–394.
- [4] Manurung R., Ritchie G., Thompson H., *Using Genetic Algorithms to Create Meaningful Poetic Text*, Journal of Experimental & Theoretical Artificial Intelligence, Vol. 24, Issue 1, 2012, 43–64.
- [5] Manurung H.M., *An evolutionary algorithm approach to poetry generation*, Doctoral Thesis, Institute for Communicating and Collaborative Systems, School of Informatics University of Edinburgh, 2003.
- [6] Araki K., Kuroda M., *Generality of Spoken Dialogue System using SeGA-IL for Different Languages*, Systems and Computers in Japan, Vol. 35, No. 12, 2004.
- [7] McIntyre N., Lapata M., *Plot Induction and Evolutionary Search for Story Generation*, Proceedings of the 48th Annual Meeting of the Association for Computational Linguistics, Stroudsburg, 2010, 1562–1572.
- [8] Goldberg D.E., Holland J.H., *Genetic algorithms and machine learning*, Machine learning 3(2), 1988, 95–99.
- [9] Langdon WB, Poli R. *Foundations of genetic programming*, Springer, 2002.
- [10] Melanie M. *An introduction to genetic algorithms*, Cambridge, Massachusetts London, England, Fifth printing 1999.
- [11] Ladd SR. *Genetic algorithms in C++*, Hungry Minds, Incorporated, 1995.
- [12] Deslauriers W.A., *Asexual Versus Sexual Reproduction in Genetic Algorithms*, Carleton University.
- [13] Wu Ch. H., Tzeng G.H., Goo Y.J., Fang W.C., *A real-valued genetic algorithm to optimize the parameters of support vector machine for predicting bankruptcy*, Expert Systems with Applications, 2007, Vol. 32, Issue 2, 397–408.
- [14] Keller J.M., Kopp T., *Application of the ARCS model of motivational design*, M. Reigluth (Ed.), *Instructional theories in action: Lessons illustrating selected theories and models*, Lawrence Erlbaum Associates, USA 1987.
- [15] Keller J.M., Suzuki K., *Use of the ARCS motivation model in courseware design (Chapter 16)*, [in:] D.H. Jonnassen (Ed.), *Instructional designs for microcomputer courseware*, Lawrence Erlbaum Associates, USA 1988.

Karolina Mazur

Stanisław Kuciel (stask@mech.pk.edu.pl)

Institute of Material Engineering, Faculty of Mechanical Engineering, Cracow University of Technology

COMPOSITES BASED ON RECYCLED POLYSTYRENE WASTE WITH TUFF MICROPARTICLES

KOMPOZYTY NA OSNOWIE ODPADOWEGO POLISTYRENU Z MIKROZĄSTECZKAMI TUFU

Abstract

Nowadays electric and electronic equipments are produced on a large scale, for example, personal computers. Therefore, more and more waste is recycled. To increase the strength properties of recycled materials, they are reinforced with various types of fillers such as natural. Over the last few years, fillers from tuffs of volcanic origin have been gaining in popularity. It is characterized by a low mass, high hardness, high matrix adhesion, which allow for uniform distribution of particles in the volume of the material. In this paper, composites based on recycled polystyrene waste with tuff microparticles in mass weight of 10% and 20% were produced by injection moulding. The basic mechanical properties at room temperature (+24°C) -24 and +80°C were evaluated. The aim of the study was to demonstrate the possibility of using the mineral filler particles as compatibilizer for recycled polystyrene waste of poor quality.

Keywords: mechanical properties, natural fillers, ecology, recycling

Streszczenie

Obecnie urządzenia elektryczne i elektroniczne są produkowane na dużą skalę, np. komputery osobiste. Dlatego coraz częściej odpady te są poddawane recyklingowi. Aby zwiększyć właściwości wytrzymałościowe materiałów z recyklingu, wzmacnia się je różnego rodzaju napelnierzami, np. naturalnymi. Tuf charakteryzuje się niską masą, wysoką twardością i wysoką adhezją matrycową, które pozwalają na równomierny rozkład cząstek w objętości materiału. W artykule opisano kompozyty na osnowie odpadowego polistyrenu z cząsteczkami tufu w ilości masowej 10% i 20% wytworzone w procesie formowania wtryskowego. Wykonano podstawowe badania właściwości mechanicznych w temperaturze pokojowej (+24°C) oraz w skrajnych temperaturach eksploatacji -24 i + 80°C. Celem badań była ocena możliwości wykorzystania cząstek napelnierza mineralnego jako kompatibilizatora dla recyklatu polistyrenu o niskiej jakości.

Słowa kluczowe: właściwości mechaniczne, naturalne napelnierze, ekologia, recykling

1. Introduction

One of the major challenges that have emerged in this century is the increasing amount of commercial waste. This is especially true for developed countries, due to the rapid rise in solid precipitation resulting from swift population growth, urbanization, industrialization and economic development [1]. The majority of the waste is generated from plastic waste, due to the widespread use of it in everyday life. In the last two decades increasing interest has been observed in technological equipment which generates growth in waste from electrical and electronic equipment (WEEE) [2]. Nowadays electric and electronic equipments are produced on a large scale, for example, personal computers present a medium lifetime at around 5 years and cellular phones at 2 years [3]. Thus, industry is increasingly seeking to recycle and reuse plastics for economic and environmental reasons [4]. Many publications on plastics recycling have been written [5–7]. Their authors were mainly concerned with the use of polymers compostable for everyday use.

The most commonly used WEEE materials are thermoplastic copolymers like ABS, HIPS and PC, among others. HIPS has a wide range of uses; for instance, it is used for the WEEE, production of packaging materials, automotive components, toys and medical applications [8]. It is an aromatic polymer, which accounts for approximately 18 million (6%) tonnes of the world plastics market. It is a multiphase copolymer system which is formed by polybutadiene rubber particles dispersed in a matrix structure of polystyrene. Its main advantages include good impact resistance, ease of moulding and processing, stability and low cost.

In the literature, there are not many studies on recycled HIPS, mainly reported are the results of creating HIPS and ABS blend with appropriate compatibilizers [9, 10]. However, Garcia-Ivars et al. used commercial and recycled HIPS for preparation of flat-sheet membranes. Their research showed that recycled HIPS membranes have higher permeation of flux and a more porous structure. Additionally, compared to HIPS membranes recycled membranes have better antifouling capabilities and higher humic acid rejection [11].

One of the methods of reinforcing thermoplastic copolymers is the addition of various fillers such as glass or carbon fibres, but also natural fillers such as minerals, wood and many others. The use of fillers in polymeric materials is not only dictated by lower production costs, but also by improved physical and mechanical properties, dimensional stability and heat resistance. The most popular fillers used for thermoplastic compounds added to balance stiffness: calcium carbonate, talc, wollastonite and kaolin. Calcium carbonate is the cheapest and most commonly used mineral filler. In addition to economic issues, it is also used to reduce shrinkage and achieve better surface finish. Talc addition improves the stiffness of thermoplastic compounds and provides better dimensional stability. Wollastonite, either alone or with fibreglass, helps to improve the surface finish of the products. Kaolin provides good impact modifications. The future of filler development is related to pioneering materials that are meant to replace many traditional materials.

Over the last few years, fillers from tuffs of volcanic origin have been gaining in popularity. A tuff is a kind of light, compact porous sedimentary rock belonging to the crust rocks. It consists mainly of organic grain materials bound by silica or clay. It is characterized by a low mass, high hardness and high matrix adhesion, which allow for uniform distribution of

particles in the volume of the material. Thanks to their use as a filler in polymer composites, the stiffness and hardness of the final material can be increased, as confirmed by studies [12–14]. In addition, it increases the temperature at which thermoplastic polymers can work and reduce their shrinkage.

Zmudka et al. studied the effect of volcanic tuff as a filler of thermoplastic polymers. They produced composites based on polyethylene, polyamide and polypropylene containing 10, 15, 20 wt % tuff filler. The mechanical properties, Vicat softening temperature and melt flow index were determined. They observed higher flexural modulus, higher temperature resistance, and shrinkage reduction. The composites obtained were characterized by a high flow index, which allows the injection of products with a complex shape [14].

Another important feature of polymer composites filled with tuff is a high flow index, which translates into an ease of forming products from this material using injection moulding. Yet another advantage is their low price and high availability, so that they can replace other more expensive additives such as antipyretic, pigments etc. in order to reduce production costs. Composites with tuff reinforcement can be used in electronics as friction materials and components that require increased creep and hardness. Properly ground tuffs result in polymer nanocomposites which have a very high temperature resistance and are also characterized by good mechanical properties (especially elastic range) as well as resistance to chemical and atmospheric agents.

As research shows, it is possible to use tuff as a plastic compatibilizer. Kuciel et al. confirmed that the addition of 5% mineral filler to PEHD recyclate improves the miscibility of waste polyolefins, increasing more than twice the strain at break, with almost unchanged strength. The obtained test results make natural mineral fillers like tuff an interesting alternative to expensive additives [12].

In this study, composites based on recycled polystyrene waste with 10 wt % and 20 wt % tuff microparticles were produced. The research part of the study was aimed at determining the basic mechanical properties of composites at room temperature (24°C) as well as extreme operating temperatures of -24 and +80°C. The values of lowered and elevated temperatures reflected the lowest and the highest temperatures at which recycled polystyrene waste composites can be used. Additionally, an analysis of the microstructure of the tuff particles and the adhesion to matrix was performed using a scanning electron microscope (SEM). Also the influence of tuff as an additive for improving miscibility was evaluated.

2. Experimental

The recycled polystyrene waste from technological waste of high-impact polystyrene (HIPS) from the KLGS plant in Mysłenice (Poland) was used as a matrix. Recycled HIPS was obtained from disassembly of obsolete monitors and keyboards previously used as parts of personal computers.

As a filler tuff supplied from a mine in Filipowice (Poland) was used. Tuff is a solid pyroclastic rock, consists mostly of minerals such as sanidine, kaolinite, illite, biotite and

quartz. The particle size in a range of 5-20 μm were obtained by grinding on a Retsch ZM 200 mill, which after grinding was rinsed in 1 molar hydrochloric acid and then calcined at 800°C.

Standard dumbbell samples were manufactured on the Engel ES 200/40 HSL injection moulding machine in accordance with PN-EN ISO 3167 standard with no previous process of extrusion and regranulation. The parameters of the injection process were as follows:

- ▶ zone temperature: 230 [°C], 235 [°C], 240 [°C], 245 [°C],
- ▶ a speed of screw rotation: 50 [rpm],
- ▶ mould temperature: 50 [°C],
- ▶ injection pressure: 80 [MPa],
- ▶ injection time: 2 [s],
- ▶ a holding pressure time: 5 [s],
- ▶ cycle time: 45 [s],
- ▶ cooling time: 25 [s].

The mechanical properties were obtained by using a universal MTS Criterion 43 (30 kN force capacity) testing machine with an MTS axial extensometer at room temperatures (24°C), -24 and +80°C by putting samples in a thermal chamber (Instron) for 30 minutes. The values were obtained from an average at least of 5 specimens. The tensile test (tensile strength (σ_M), modulus of elasticity (E_f) and strain at break (ϵ_B)) was carried out according to the ISO 527 standard with a constant cross-head speed of 5mm/min. The flexural three-point bending test (flexural modulus (E_f) and flexural stress at 3.5% strain (σ_f)) was performed with a constant cross-head speed of 5 mm/min (ISO178).

A Charpy impact test (ISO 179-1) was carried out using a Zwick/Roell HIT5.SP testing machine on unnotched samples. The microstructure of the obtained composites was observed with a JEOL JSN5510LV scanning electron microscope on gold-sputtered fracture surfaces specimens.

3. Results and Discussion

The symbols and mechanical properties determined in the tensile test for samples under standard condition are shown in Table 1. It can be observed that the elastic modulus increased proportionally to the increasing of tuff content. The addition of 20 wt % tuff led to an approx. 30% increase in stiffness, which is the observed effect of adding mineral fillers. The tensile strength slightly decreases by approximately 5% remaining constant with increasing amounts of tuff microparticles in the composite. There were no significant changes for deformability.

Figures 1, 2 and 3 show the comparison between the basic strength properties determined by the static tensile test of recycled polystyrene waste and its composites with 10 wt % and 20% tuff particles at room temperature (24°C) as well as extreme operating temperatures of -24 and +80°C. Addition of tuff particles had no significant influence on the tensile strength of composites. However, for all the tested materials the tensile strength was higher at the lower temperature of -24°C but at the higher temperature +80°C was the lowest. Addition of tuff

Table 1. Symbol of composite and mechanical properties of the tested materials

| Sample | Composition [wt%] | σ_M [MPa] | E_i [MPa] | ϵ_B [%] |
|--------|---------------------------------|------------------|-------------|------------------|
| PS | Recycled polystyrene waste | 40.1±0.87 | 3460±49 | 1.5±0.06 |
| PS/10T | Polystyrene +10% tuff particles | 37.3±1.80 | 3960±205 | 1.6±0.05 |
| PS/20T | Polystyrene +20% tuff particles | 38.2±0.16 | 4400±199 | 1.4±0.25 |

particles increased the modulus of elasticity for composites proportionally to the increasing of tuff content at all temperatures and the higher is at -24°C. The highest over double increase in deformation compared to PS was observed at +80°C, which is a favourable phenomenon and relatively rarely observed. Probably the developed surface of the hard filler microparticles increases the friction forces between them and the polymer matrix during the tensile test.

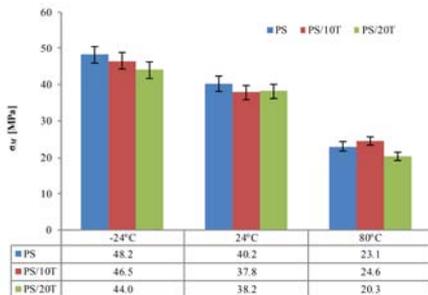


Fig. 1. Tensile strength for PS, PS/10T, PS/20T at room temperature (24°C), -24 and +80°C

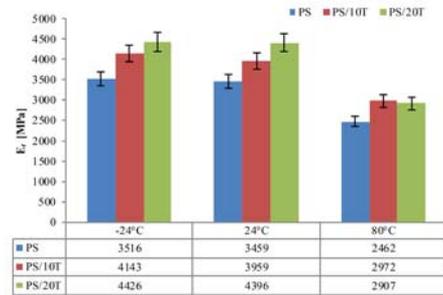


Fig. 2. Modulus of elasticity for PS, PS/10T, PS/20T at room temperature (24°C), -24 and +80°C

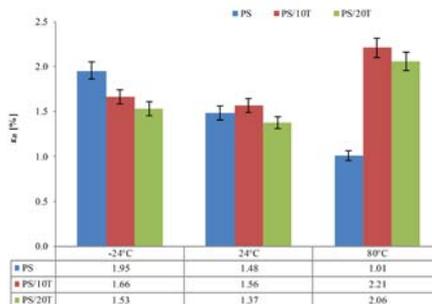


Fig. 3. Strain at break for PS, PS/10T, PS/20T at room temperature (24°C), -24 and +80°C

Figures 4 and 5 compare the static bending test results obtained with PS, PS/10T and PS/20T strength tests at room temperature (24°C), -24, +80°C. The value of the elastic modulus increased in proportion to the increase in tuff content in the composite over the entire range of temperatures tested. Bending strength increased especially at elevated temperatures +80°C, and slightly decreased at low temperatures.

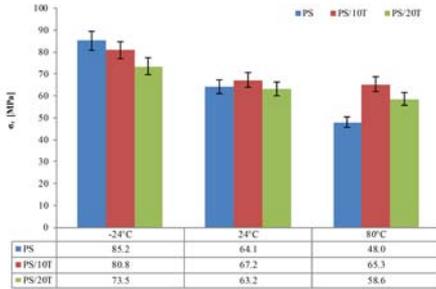


Fig. 4. Flexural stress at 3.5% strain for PS, PS/10T, PS/20T at room temperature (24°C), -24 and +80°C

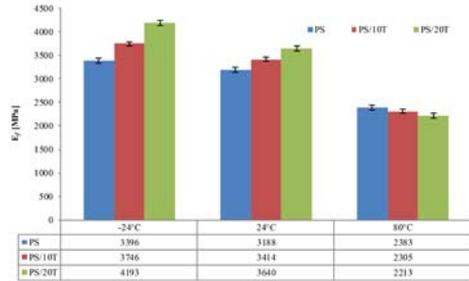


Fig. 5. Flexural modulus for PS, PS/10T, PS/20T at room temperature (24°C), -24 and +80°C

Figure 6 shows the results obtained in the impact test for polystyrene and its composites with 10 wt % and 20 wt % tuff particles. At room temperature, the addition of tuff particles did not significantly change the impact test result. A significant threefold increase in impact strength for samples PS/10T at an elevated temperature of + 80°C was observed. This demonstrates the improvement of homogeneity of polystyrene recycle and improvement in the impact strength, which increases the possibility of its various applications for technical products. At lower temperatures, there was a 30% decrease in impact strength for composites, and its values for PS/10T and PS/20T composites were similar.

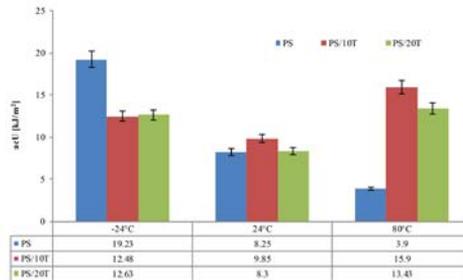


Fig. 6. Charpy impact strength for PS, PS/10T, PS/20T at room temperature (24°C), -24 and +80°C

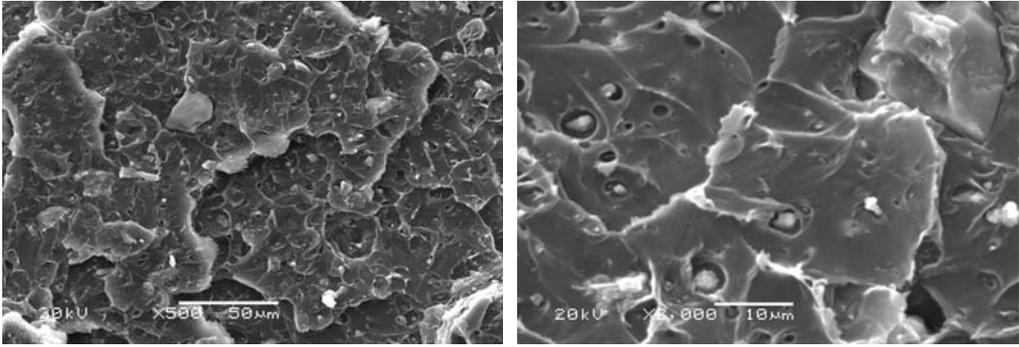


Fig. 7. SEM images of PS/20T tensile test fracture surfaces

Figure 7 show SEM images acquired on tensile fracture specimens of PS with 20% of tuff microparticles. Good homogenization of tuff particles uniformly deposited on the surfaces of the crystalline polystyrene can be observed. The surface of a brittle fracture is related to the supermolecular structure of polystyrene and the method of its crystallization and microparticles are loosely embedded in the polymer matrix.

4. Conclusion

The volcanic tuff microparticles proved to be an interesting modifier for recycled polystyrene waste leading to a significant 30% increase in the modulus of elasticity, maintaining the level of strain at break and only a slight decrease of a few percent in tensile strength.

The unchanging value of deformation at break is an extremely beneficial and rarely observed phenomenon; it is caused by the developed surface of tuff microparticles and confirms the compatibility of their effect on polymeric mixtures [15]. The consequence of these phenomena is a favourable increase in impact strength, especially at elevated temperatures.

The results of the study indicate that it is possible to produce composites based on recycled polystyrene waste matrix modified by rocks of volcanic porous origin with increased stiffness and impact resistance. This is of particular importance for the management of poor quality polystyrene waste from various sources, which is difficult to manage because of the significant deterioration in properties due to fluctuations in properties due to aging and compositional homogeneity. Tuff microparticles act as a physical compiler, which promotes miscibility by resolving micro-regions of polymers with different properties, which increases the deformability of the composites produced and their impact resistance. Various applications of polystyrene waste of poor quality for technical items and products with low aesthetic requirements can be indicated, which, thanks to the addition of a new mineral compatibilizer, will have better endurance properties.

Figure 8 shows one example of the possible disposal of recycled polystyrene waste extruded profiles with the addition of wood fibres. These profiles are more durable and less flammable than wood. It works well under wet conditions and at low temperatures. It has a high level of UV resistance and is resistant to fading. The addition of tuff to such a composition will improve its miscibility with wood fibre, and increase its stiffness and impact resistance.



Fig. 8. Example of fence made of waste polystyrene [16]

Summarizing, poor quality recycled polystyrene waste with the addition of a cheap mineral compatibilizer, tuff of volcanic origin, can become a sought after waste that can be used in combination with fibres or alone for long life products. This increases the possibilities of recyclable material of such waste and enables better use of natural resources.

References

- [1] Mudgal S., Lyons L., Kong M.A., *Study on an Increased Mechanical Recycling Target for Plastics*, Final Report Prepared for Plastic Recyclers Europe: Bio-Intelligence Service, 2013.
- [2] Vazquez Y.V., Barbosa S. E., *Process Window for Direct Recycling of Acrylonitrile-Butadiene-Styrene and High-Impact Polystyrene from Electrical and Electronic Equipment Waste*, *Waste Management*, 2017, 403–408.
- [3] Hirayama D., Saron C., *Morphologic and mechanical properties of blends from recycled acrylonitrile-butadiene-styrene and high-impact polystyrene*, *Polymer*, 2018, 271–278.
- [4] Selke S.E., *Plastics Recycling and Biodegradable Plastics*, *Handbook of Plastics Technologies*, McGraw-Hill, 2006.
- [5] Ren X., *Biodegradable plastics: a solution or a challenge?*, *Journal of Cleaner Production*, 2003, 27–40.
- [6] Long J., Jinwen Z., *7 – Biodegradable and Biobased Polymers*, *Applied Plastics Engineering Handbook (Second Edition)*, 2017, 127–143.
- [7] Syed A.A., *5 – Types of Biodegradable Polymers*, *Introduction to Bioplastics Engineering*, 2016, 81–151.
- [8] Bekri-Abbes I. , *Converting Waste Polystyrene into Adsorbent: Potential Use in the Removal of Lead and Cadmium Ions from Aqueous Solution*, *Journal of Polymers and the Environment*, 2006, 249–256.
- [9] Vazquez Y.V., Barbosa S.E., *Recycling of mixed plastic waste from electrical and electronic equipment. Added value by compatibilization*, *Waste Management*, 2016, 196–203.

- [10] Hosseini S.M., Madaeni S.S., Khodabakhshi A.R., *Preparation and characterization of ABS/HIPS heterogeneous cation exchange membranes with various blend ratios of polymer binder*, Journal of Membrane Science, 2010, 178–188.
- [11] Garcia-Ivars J., Wang-Xu X., Iborra-Clar M.I., *Application of post-consumer recycled high-impact polystyrene in the preparation of phase-inversion membranes for low-pressure membrane processes*, Separation and Purification Technology, 2017, 340–351.
- [12] Kuciel S., Kuźniar S., Mięka J., *Tuf – nowy mineralny kompozytizer recyklatów PHED przeznaczonych do wytwarzania wyrobów metodą rozdmuchiwania*, Przetworstwo Tworzyw, 2013, 250–258.
- [13] Żmudka S., Kuciel S., *Europalety z recyklatów poliolefin wzmacniane wulkanicznym tufem*, [in:] *Materiały Polimerowe 2010*, ed. T.&S. Spychaj, Szczecin 2010, 731–733.
- [14] Żmudka S., Budniak I., Kuciel S., Mięka J., *Ocena możliwości zastosowań wulkanicznego tufu jako wypełniacza polimerów termoplastycznych*, Czasopismo Techniczne, 1-M/2009, 421–428.
- [15] Kuciel S., Mięka J., *Tuf jako kompozytizer – promotor mieszalności recyklatów polimerów i kompozytów włóknistych oraz termoplastycznych mieszanin wielopolimerowych*, Patent.394848, Pub.30.09.2015.
- [16] lowcarbonproducts.wordpress.com (access: 5.02.2018)

