Technical Transactions

Czasopismo Techniczne

Contents

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Marcin Brzezicki orcid.org/0000-0002-3901-144X
marcin.brzezicki@pwr.edu.pl
    Wroclaw University of Science and Technology

Glass protected timber façades –
new sustainable façade typology

Fasady drewniane chronione przez szkło –
nowa ekologiczna typologia fasad

Abstract

It is increasingly common in the architecture/building industry that glass is placed in the front of the proper façade and serves as a protective layer for the wall behind. This type of external glazing is also used as an envelope for timber façades. External protection by glass slows down timber decomposition and weathering as it screens out potentially dangerous climatic factors like rain, moisture, and frost. Timber-behind-glass is becoming one of the most promising typologies in façade design from a sustainability perspective. The presented paper discusses this new emerging architectural trend. The combination of timber and glass is expected to produce both very durable (long service-life) and simultaneously environmentally friendly façade as timber locks CO_2 into its substance.

Keywords: timber façade, building glass, double leaf façade

Streszczenie

Coraz częściej w architekturze szkło jest umieszczane przed właściwą fasadą i służy jako jej zewnętrzna osłona. Ten rodzaj szklenia jest również stosowany jako zewnętrzna obudowa fasad drewnianych. Szklana tafla spowalnia starzenie drewna i jego degradację, ponieważ eliminuje potencjalnie niebezpieczne czynniki klimatyczne, takie jak deszcz, wilgoć i mróz. Drewno-za-szkłem staje się jedną z najbardziej obiecujących typologii w projektowaniu elewacji z perspektywy zrównoważonego rozwoju. Przedstawiony artykuł omawia pojawiający się w architekturze nowy nurt. Można się spodziewać, że połączenie drewna i szkła będzie skutkowało zarówno bardzo trwałą, jak również bardzo przyjazną dla środowiska fasadą, ponieważ drewno wiąże na trwałe CO_2 w swojej masie.

Słowa kluczowe: fasada drewniana, szkło budowlane, fasady podwójne

1. Introduction

Timber is becoming popular as it is recognized as an environmentally friendly alternative to several high-carbon-footprint building solutions [21]. The reason for this is the fact that biomaterials can efficiently sequester carbon during biomass growth (one tonne of CO_2 per cubic meter of wood [10]) and – after their service life period is finished – can decompose into the environment without any waste. Nowadays timber is also a subject of cutting-edge technological inventions like large-scale lamination (dating back to 1950. in the 20th century but has been constantly improving ever since), different surface treatments (acetylation, furfurylation) [20] and a new range of innovative bio-based façade materials [19].

Nowadays, timber is gradually becoming an increasingly important building material, especially in the context of a CO_2 neutral economy. It is frequently said – also in popular culture – that "timber is the new concrete" [7]. Currently, timber-based building technologies are gradually replacing cement-based technologies, especially in selected structural applications. After a period of tragic fires in 19th century cities, new building regulations were imposed that are now seen as outdated and "inhibiting the construction of taller wooden structures in many countries" [10]. With the advent of new timber treatment technologies – basically glulam and cross-lamination – timber gradually became "economically attractive again and introduced a new dynamic" after strict regulations were dropped [21]. Fire requirements are usually met by (i) the over-dimensioning of timber members, (ii) additional gypsum-board cladding, or (iii) the use of sprinklers.

It is common in architecture for glass to be located in the front of the proper façade serving as a protective layer for the wall behind. This type of external glazed envelope does not necessarily contribute to the building's illumination – glass also faces so-called "blind wall" sections – therefore this façade typology is called *redundant* [4]. This layered type of façade originated as a tool of microclimate regulation in double skin façades – the space between glass and façade is utilized as a thermal buffer that slows down heat exchange – but gradually developed as an independent aesthetical trend in contemporary architecture.

The presented paper discusses a rare combination of the two aforementioned technologies, where glazing is used as **an external envelope for the timber-clad façade**. In this arrangement, glass gains a new function. It slows down timber decomposition and weathering as it screens out potentially dangerous climatic factors like rain, moisture, and frost. This emerging architectural trend for the purpose of the presented paper is tentatively named *timber-behind-glass. Timber-behind-glass* façade morphology originated in façade design. It was the innovative approach to façade design that led to the creation of multi-layered systems dating back to the beginning of the 21st century [16] which then gradually evolved into redundant typologies where glass is used mainly as an external envelope but sometimes clearly as an aesthetical tool [4]. *Timber-behind-glass* façade morphology has not been identified directly in scientific research yet. Therefore no straightforward references can be made so far.

2. State of the art

The use of an external layer of glass is considered to be a tool of formal expression in architecture, as it provides additional depth to the façade. In this context, the issue has been analyzed by numerous theoreticians of architecture. The discussion was initiated by the paper *Transparency: literal and phenomenal* published in 1963 defining so-called "shallow space" as a by-product of façade layer stratification [18]. The most exhaustive review of glass façades is given in the book Engineering Transparency [1] that features papers by architecture theoreticians including Keneth Frampton and Beatriz Colomina. In 2014 one author published an article defining a new type of transparency in architecture named "redundant transparency" [4]. The paper described the emerging creative trend of using light-permeable materials in the spandrel portion of the façade, allowing the materials to "simultaneously maintain their essential property of light transmission and enrich the spatial depth of the façade" [4]. This study of the light-transmitting building envelope in conjunction with raising environmental awareness became a direct inspiration for the presented paper.

An exhaustive study of both glass and timber façades is available and easily accessible. The comprehensive study of glass façades titled *Facade construction manual* is given by Herzog, Krippner, & Lang [8] but the façades are addressed in a general manner, with some remarks on the timber technologies. The same author published a comprehensive guide to timber structure design in architecture, including timber façades and cladding, titled *Timber construction manual* [9]. Both books were published more than 10 years ago.

Knaack et al. published the book *Façades: principles of construction* [12] which become one of the most valuable resource books on the subject of façade design. The book also features intelligent and adaptive double-skin façades. In building performance and engineering, much attention has been addressed to the consideration of timber façade elements like windows and doors especially in the context of the timber service life (Surmeli-Anac, 2013) but no extensive study on timber protected by glass has been done yet.

3. Research methodology

The term "morphology" for the description of the way that the façade is built was introduced by Moloney [15] in the book titled *Designing Kinetics for Architectural Facades: State Change*. The term originated from the field of biology, where word "morphology" is used to describe the spatial relations of the elements of a living organism, while "physiology" describes the way it works. Morphological analysis was a default research method adopted in the presented paper. This method of analysis separates the elements of the analyzed façade system into individual components and classifies them according to the function fulfilled, assigning it a "physiological" purpose – a function. In the presented study, initial morphological studies of timber and glass façades have been based on the photographs, on-site measurements, and inspections performed during field trips and on iconographic materials. All façades featured in the presented photographs were visited by the author. After being distinguished, the

morphological features of the façades served as a formulation of an initial typology of *timber-behind-glass* façade systems. In the following chapters, the typology is presented first, while the case studies are described afterward.

4. Typology

It must be stated, that *timber-behind-glass* façade typology is not yet clearly defined in literature and – despite the presented trials – still requires extensive desk-study research to determine all the cases of application. However some typological regularities might be distinguished based on the analyzed case-studies. This façade typology is becoming more and more common and was used – in different settings – by many architects. Timber-behind-glass façade typology is constantly developing, delivering new solutions.

The general spatial organization of *timber-behind-glass* façade typology features, quite obviously, **a pane of glass positioned at the front of a timber façade**, usually – but not exclusively – parallel to each other. Therefore glass forms the external layer and timber cladding – internal. From a "morphological" perspective different possible distances between the timber cladding and glass are possible, so a **cavity of a different** depth and volume is created (Fig. 1). This constitutes a basic typological factor for *timber-behind-glass* façades, that is also closely connected to the air circulation described in detail below. Also, single, or double glazing might be used, as well as different types and geometries of glass. This geometrical diversity is typical for the works of architecture.

From the "physiological" point of view, the typological approach is more complex as featured case-studies might be divided according to many factors/parameters. The most influential one from a functional perspective is **air circulation**. Therefore *timber-behind-glass* façades might be divided into (i) sealed- and (ii) ventilated envelopes.

- ▸ In sealed envelopes, the timber façade is separated from the external environment and works in constant microclimatic conditions, usually the same as the building's internal ones. Glazing forms a continuous sealed envelope covering the entire façade or even the whole building. The distance between the sealed glass envelope and the timber cladding might be different, spanning from a few centimeters to over a dozen meters in case of glazed winter gardens and atria (see the previous paragraph addressing different cavity size).
- ▸ In ventilated solutions, the timber façade is usually protected only from rain, while air circulation remains possible, therefore the timber is exposed to external temperature, frost and humidity fluctuations. The location of ventilation openings might be different – similarly – as in double leaf façades. The apertures might be located at the bottom and at the top of the façade, or the openings might be regularly scattered over the whole surface. The air flow can be determined by the size of the openings: narrow slits would allow only for limited air exchange while wide gaps would facilitate extensive drafts.

The other factor influencing the functional performance of the façade is the **interior illumination**. Usually, glass covers the entire façade, regardless of the windows located in the internal timber layer. In certain sections, glass is juxtaposed with the so-called "blind wall". This allows the division of sections of the façade into (i) daylight active – permitting daylight deep into the room or (ii) redundant – glazed, but not contributing to the building's illumination. Therefore possible solutions range from daylight active façades, where light penetrates the building through numerous layers of glass, and redundant, where only a relatively shallow space is illuminated, the space between the external glazed envelope and the solid timber-clad wall.

The possible variation of the timber-behind-glass typology is presented in Fig. 1.
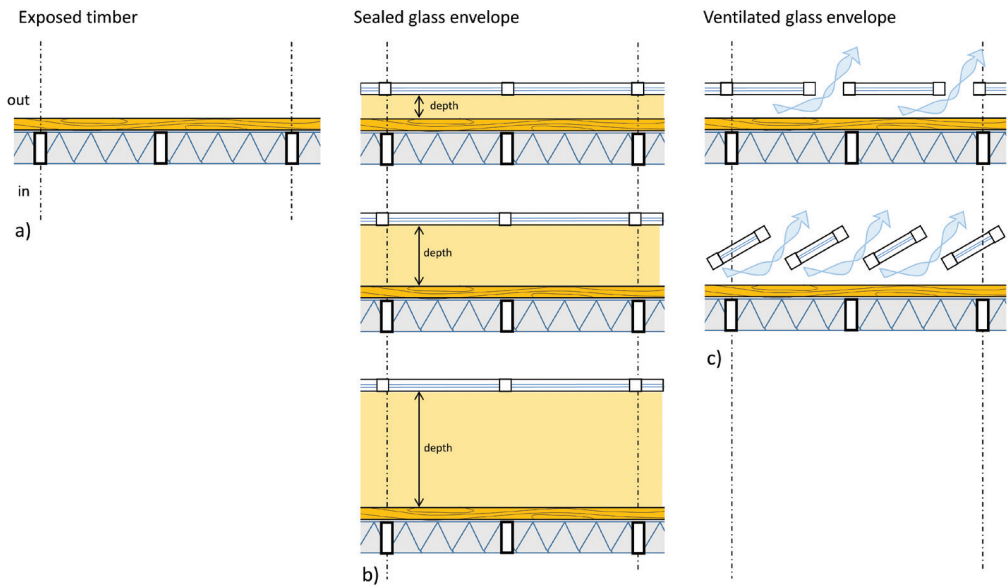
Fig. 1. Schematic diagram of the typology of timber-behind-glass façades; a) shows unprotected timber cladding, b) shows a sealed glass envelope and timber cladding behind. The different depths of the cavity are illustrated by a yellow hue, c) pictures different variations of ventilation strategy: shown in plan and section views. Diagram by author

5. Case studies

Air circulation was assumed to be a basic functional or "physiological" factor defining different types of timber-behind-glass façades. Façade depth and interior illumination are important but seem to be a secondary factor.

5.1. Sealed envelopes

With the increasing amount of timber used for structural purposes, cases of the sealed *timber-behind-glass* façades are becoming more common. Recently, in selected countries, timber gained positive fire ratings allowing for the use of massive exposed laminated elements

for structural purposes (e.g. in Switzerland). This relatively novel application of traditional material is considered an advantage in many buildings, therefore architects are eager to expose the natural texture and quality of the timber.

The glazed curtain wall is regarded as a standard material in office buildings. Those two – timber and a sealed glazed curtain wall – are matched to create new formal appeal. These cases of façades start with a relatively small depth of façade cavity – a few centimeters – that is usually defined by standard façade-to-structure solutions. In this typology, one of the most prominent recent case studies is the Tamedia building in Zurich (arch. Shigeru Ban, 2013, Fig. 2) where the timber structure is vaguely seen through the glazed envelope or the FrameWork building in Portland (arch. Works Partnership Architecture, 2015). Another – even more interesting but dating back to the year 2000 – is the GC Osaka Building, also by Shigeru Ban (arch. Shigeru Ban, 2000, Fig. 3) where 50 mm thick timber is used as a "flammable barrier" cladding for steel structural elements [6]. The whole structure is enveloped in a glazed curtain wall from the bottom to the top of the building, clearly showing timber elements through the glass, as glass panes are also used in the spandrel areas of the façade.

Fig. 2. Tamedia building in Zurich (arch. Shigeru Ban, 2013). Photo by author

Fig. 3. GC Osaka Building (arch. Shigeru Ban, 2000). Photo by author

Increasing cavity depth allows for more elaborate chiaroscuro effects. In the well-known case study of Bibliothèque nationale de France (arch. Dominique Perrault, 1989, Fig. 4) timber shutters located directly behind the glass create an impressive sculptural effect of what is basically boring planar glass façade. A similar effect, but not as elaborate, is visible in the case of the Oskar von Miller Forum in Munich (arch. Herzog + Partner, 2000, Fig. 5), where veneer laminated shutters are used to regulate daylight penetrating into the building. Because of the serrated geometry of the glazed envelope itself, the visibility of the timber depends on the observer's viewpoint.
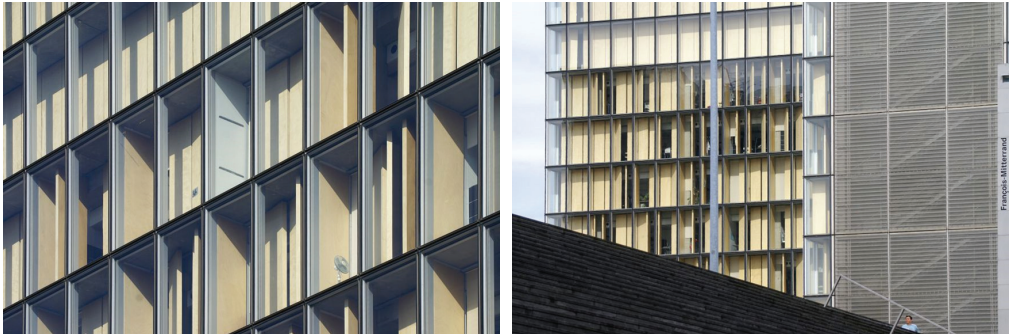
Fig. 4. Bibliothèque nationale de France (arch. Dominique Perrault, 1989). Close up of the tower façade. Photo by author

A large atria allows the observation of the timber façade from a wider perspective. In those cases the enlarged cavity – the distance between glazed envelope and timber cladding – is frequently used as a circulation space, so the users can interact with the timber cladding and enjoy the space. Academy Mont-Cenis in Herne (arch. HHS Planer, 1999), CDU party HQ in Berlin (arch. Petzinka, Pink and Partners, 2000, Fig. 6a) and Oslo Opera (arch. Snohetta, 2007, Fig. 6b) are the most prominent examples of large glazed envelopes that encompass the
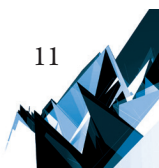
entire building. They are also called *cloches* (*cloche* – meaning the bell jar in French). *Cloches* are basically used for climatic purposes, but the timber protection comes as an additional advantage. One of the most recent examples in San Sebastian's academic library "Carlos Santamaría Centre" (arch. JAAM, 2011, Fig. 7), where the entry atrium "which opens up like a large mouth, pointing the vertex towards the sky" [5] is clad in timber and externally glazed forming a very high quality of circulation space.

Fig. 5. Oskar von Miller Forum in Munich (arch. Herzog + Partner, 2000). Photo by author
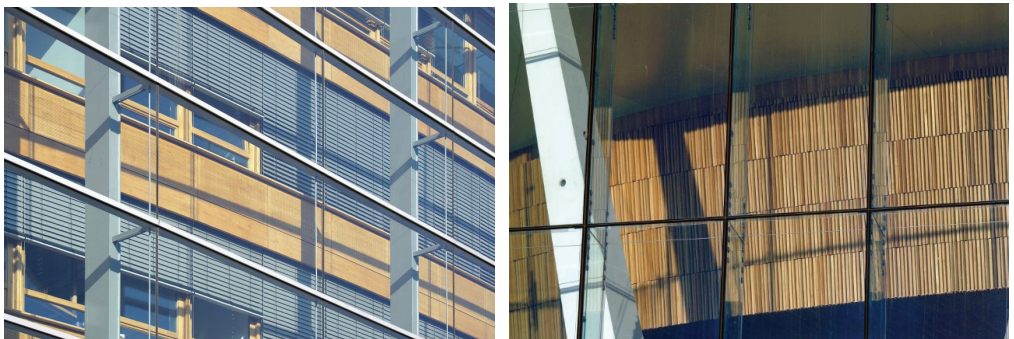
Fig. 6. a) CDU party HQ in Berlin (arch. Petzinka, Pink and Partners, 2000) and b) Oslo Opera (arch. Snohetta, 2007). Photo by author

Fig. 7. San Sebastian's academic library Carlos Santamaría Centre (arch. JAAM, 2011). Photo by author

5.2. Ventilated envelopes

The examples of *timber-behind-glass* applications in ventilated envelopes range from the classic double-skin-façades to complicated bespoke design ventilated envelopes.

The application of timber in double façades usually involves timber-framed internal glazing or the cladding of ventilation openings. This morphology was quite frequently used over the last two decades, with examples in Munich in the Mercedes-Benz Centre (arch. Lai Architekten, 2002, Fig. 8) or in Frankfurt am Mein in the façade of the H1 building of the University of Applied Sciences (arch. Heribert Gies Architekten, MainzVoigt & Herzig Architekten & Ingenieure, 2007, Fig. 9). The timber in the last case-study was clearly chosen as "pleasant material", rather than as an environmentally considered solution [3]. Beyond the aesthetic impression, the double façade was of course used for building microclimate

regulation. A similar solution, but with a serrated glass arrangement for a more dynamic air exchange, was designed in an office building located at Hammerstrasse 19 in Düsseldorf (arch. Petzinka Pink Architekten, 2000, Fig. 10) and in the refurbishment of Bayerische Vereinsbank in Stuttgart (arch. Behnisch & Sabatke, 1969 i 1997, Fig. 11). Especially in the latter case, "a double-leafed façade was (…) proposed (…) as part of the building's new climatic strategy. The result is a completely different aesthetic and a building which operates in a more environmentally responsible manner" [1]. Apart from this, the proper façade of the building has been clad with wooden planks.
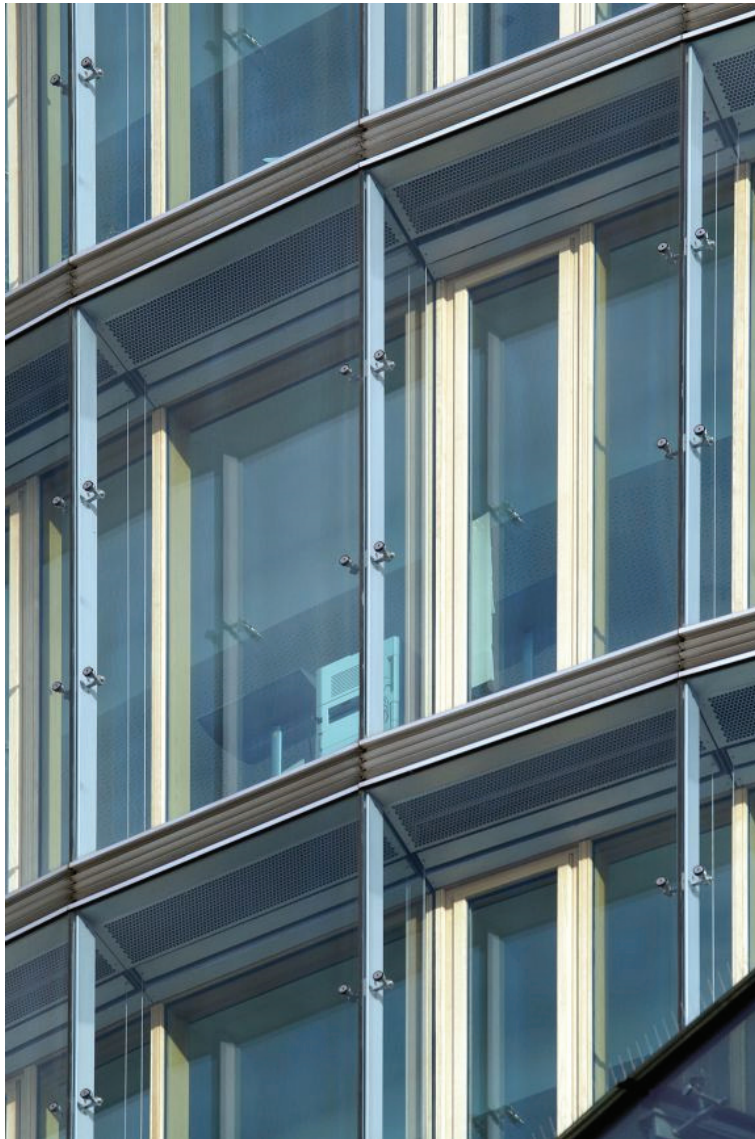
Fig. 8. Mercedes-Benz Centre in Munich (arch. Lai Architekten, 2002). Photo by author
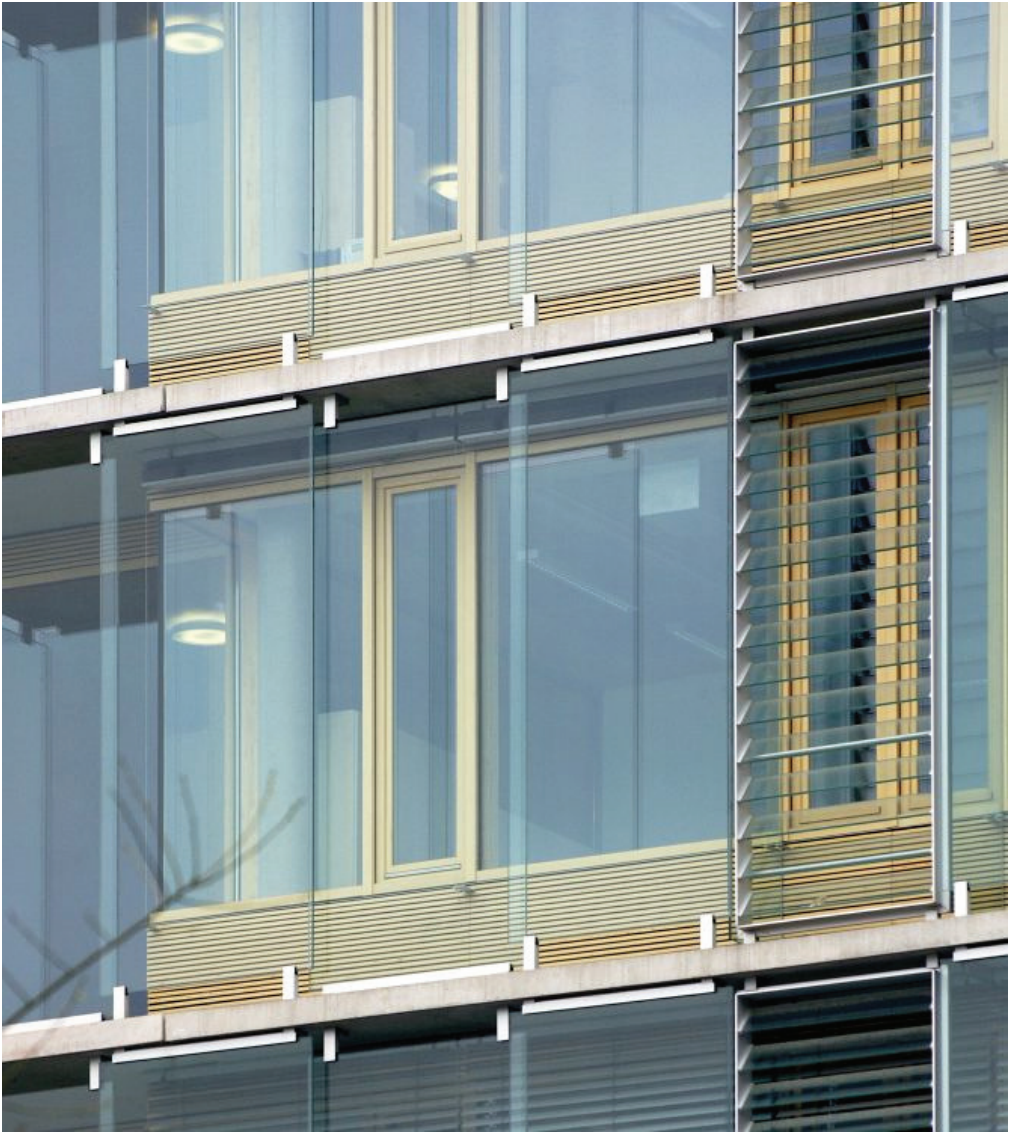
Fig. 9. H1 building of the University of Applied Sciences in Frankfurt am Mein (arch. Heribert Gies Architekten, MainzVoigt & Herzig Architekten & Ingenieure, 2007). Photo by author

Beyond the standard double-leaf façade, some custom designed solutions are present. The most striking is the use of the external glazed envelope in Rheinisches Landesmuseum in Bonn (arch. Knut Lohrer, 2003, Fig. 12). The existing building extension was clad in massive timber elements, that is externally protected by a large ventilated pane façade that is cable hung from above. Thin vertical slits between the panes of glass allow for air exchange between the external and intermediate spaces surrounding the building. Another striking contemporary example of this typology is the research institute in Cerdanyola del Vallès (arch. Harquitectes
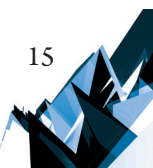
Dataae, 2017). The building is designed to function in the hot and humid climate of Catalonia, therefore "architects grouped insulated wooden cubes around four atriums that serve as buffer zones. An economical industrial greenhouse system encloses the entire block in polycarbonate panels that can be opened" [17]. Despite glass not being used, the whole system works as in a classic *timber-behind-glass* arrangement, but additionally, the external layer of the façade is adaptive, as it opens and closes depending on the weather and the season of the year. The internal cubes are clad in 16 mm plywood, which is a relatively fragile material when exposed to external conditions. The application of the external ventilated envelope allows the use of bio-based veneer elements as external cladding.
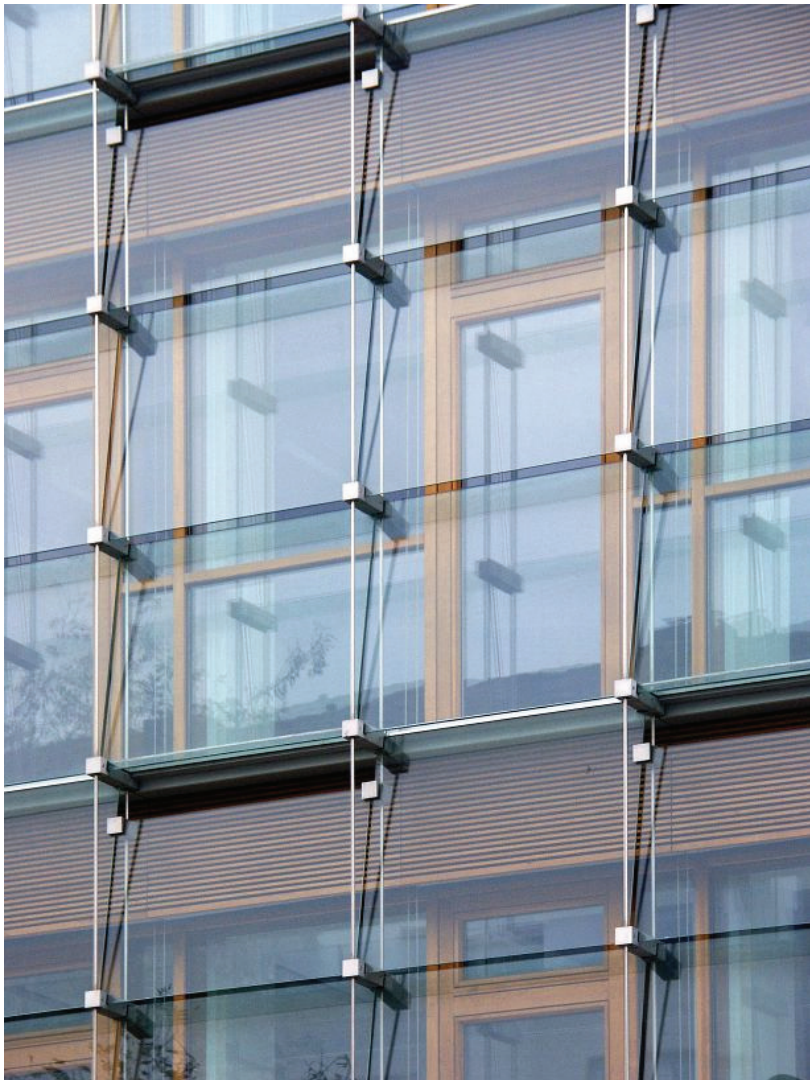
Fig. 10. Office building in Hammer strasse 19, Düsseldorf (arch. Petzinka Pink Architekten, 2000).
Photo by author

Fig. 11. Bayerische Vereinsbank in Stuttgart (arch. Behnisch & Sabatke, 1969 and 1997). Photo by author
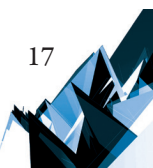
Fig. 12. Rheinisches Landesmuseum in Bonn (arch. Knut Lohrer, 2003). Photo by author

Another striking and fairly recent example of the ventilated *timber-behind-glass* morphology is a Market Hall in Ghent (arch. Robbrecht en Daem Architecten & Mjose Van Hee Architecten, 2012, Fig. 13). This is a newly constructed roof covering a rectangular event space in the center of the medieval city. The new building replaced the parking lot, that previously existed on the site. A steel roof that is "5-times folded" looks like a capital letter "M" in section view. The load-bearing steel structure is clad with timber. The external timber cladding is covered by the glass tiles from the outside – "a glass envelope protects the wood and provides a soft shine, with the sky reflected, integrated" [14]. *Timber-behind--glass* morphology is used all over the building – in the sloping sections of the roof and on the vertical sections of the wall. Tiny translucent rectangular windows are embedded in the timber cladding allowing light to penetrate inside the building.

Fig. 13. Market Hall in Ghent (arch. Robbrecht en Daem Architecten & Mjose Van Hee Architecten, 2012).
Photo by author

6. Discussion

The case-studies presented above feature glass envelope and timber cladding in different spatial arrangements. It has to be clearly stated, that in many of them the external glazed envelope was not deliberately planned as a weather screen for timber. It merely fulfills this function as a by-product of the façade morphology, usually aesthetically or climatically motivated. This spontaneous *timber-behind-glass* architecture trend does not seem to be organized in any considered way, rather it occurred in many places simultaneously over the course of the past 20 years.

Currently, with rising environmental awareness, we can benefit from the already existing trend by examining the cases of application and discovering the new potential of this façade morphology. This new potential lies in the reduction of the building's carbon footprint, both by reducing its energy use (the climatic competent) and by extending the service life of the timber. External glazing serves a protective layer for the timber, but it also decreases the number of chemicals used for timber conservation and reduces the environmental load. Both issues open wide possibilities for future applications.

Based on the given case-studies, it is also clearly visible, that ventilated *timber-behind-glass* systems were used in buildings with ventilated façades, mainly at the beginning of the first decade of the 20th century. Currently, increasing energy performance requirements demand air-tight envelopes to be developed and designed and central air-exchange systems with heat
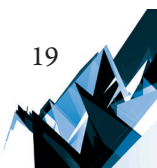
exchangers to be used as postulated by German Passivhaus standard. New requirements do not necessarily mean that ventilated timber-behind glass morphology cannot be used. It still presents a wide range of possible applications if located externally in relation to the air-tight membrane. Glass located as an external protective layer for vulnerable bio-based materials will provide protection and extend the service life of timber cladding.

7. Further research – sustainability perspective

Further research into the subject of *timber-behind-glass* façade morphologies opens a new perspective of both sustainable (timber or bio-based cladding) and durable (glass) composites. Timber and glass used in proper combination will allow substantial improvement of the durability of a bio-based façade structure or cladding, simultaneously defining new features as a result of synergy and compensating their potential drawbacks. An architectural *timber--behind-glass* façade will substantially reduce the timber maintenance effort as the glass will constitute the protective layer for timber [11]. It is also expected that – at the "disposal" stage of the façade's life cycle – the timber will be in a condition to either allow for cascade use (use of timber for other applications, e.g. for particle boards) or for recycling (bio-decomposition of timber). The combination of glass and timber – two materials of very different LCA – might also have a compensatory effect (timber, the lower LCA material will compensate glass, the environmentally higher LCA material). As two materials of very different carbon footprints are combined in one solution, the optimal environmental outcome is hoped to be achieved [13].

The main degradation factors for timber are both abiotic: moisture, UV radiation, as well as biotic factors: fungus and molds. Improved moisture management and air circulation give a solid ground for the assumption that the service life of timber cladding will be comparable to the timber elements used in interiors. Blocking UV radiation might also substantially improve the service life of the timber. Use of selective glazing – UV-selective glass – might slow down the destructive process of timber photolysis [22].

It is also hypothesized that *timber-behind-glass* typology has an insulation potential as the thermal buffer created between timber and glass slows down the heat exchange and facilitates the passive heat capture. A similar mechanism to double-skin-façades is expected, although it has to be taken into consideration that the air exchange rate might influence both the moisture management and the buffer's insulation potential.

8. Summary

Timber-behind-glass morphology emerged mainly as an aesthetic trend, originating from double-leaf-façades at the beginning of the 21st century. It developed independently without any theoretical grounds and was applied by different architects in buildings of different function and formal appeal. Only the recent shift towards low-carbon economy allowed

us to realise the sustainability potential of the discussed façade morphology. The generally described trend above still requires research and more detailed analysis. The presented paper is just a first approach to organize and systematize the features of the trend by outlining basic typologies that are observed in the relatively rare cases of application. The potential of the new façade morphology lies in the combination of both glass and timber in a layered arrangement. It brings new capacity for the façade industry and for the sustainability of the built environment while opening up a wealth of new architectural formal experiments.

The field study was performed with the following equipment used for photographic documentation of the buildings: Sigma EX 10-20 mm / 4-5.6 DC HSM lens and telephoto zoom lens Sony 70-300 mm f / 4.5-5.6 G SSM.

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Małgorzata Hryniewicz (iD) orcid.org/0000-0002-8034-1520
malgorzata.hryniewicz@pk.edu.pl
Institute of History of Architecture and Monument Preservation, Faculty of Architecture,
Cracow University of Technology

Cartography and landscape painting of the 17ᵗʰ and 18ᵗʰ centuries as iconographic sources

Kartografia i malarstwo pejzażowe XVII, XVIII wieku jako źródła ikonograficzne

Abstract

In the study of historical architecture, especially the one that was transformed or ruined, of key importance is iconography, i.e. views of and panoramas of cities or their parts or individual objects.

Keywords: iconographic sources, cartography, landscape painting, credibility of iconographic sources

Streszczenie

W badaniach nad architekturą historyczną, a w szczególności pozostającą w stanie mocno przekształconym lub zrujnowanym, kluczową rolę odgrywa ikonografia, czyli widoki i panoramy miast lub ich fragmentów bądź poszczególnych obiektów.

Słowa kluczowe: źródła ikonograficzne, kartografia, pejzaż, wiarygodność źródeł ikonograficznych

1. Development of European and Polish Landscape Painting

As far back as the Antiquity people were creating images of metropolises or their parts: units or individual works. However, these portrayals that were sometimes peculiar and representative of a specific artistic technique or a convention of depicting reality, are of lesser documentary value. Still, they do constitute an invaluable research materials for architectural historians.

Only in the 17th and 18th centuries brought the peak and great development of the landscape painting. This is when vedute became popular: paintings, drawings, and prints depicting panoramas and views of historic cities and buildings in them (Fig. 1) with almost photographic precision. The Dutch were precursors of this type of painting. As far back as the 17th century they introduced a perspective based on geometrical principles supported by simple optical devices such as camera obscura.

Fig. 1. Francesco Guardi – view of the Grand Canal in Venice, second half of the 17th century [6]

The fact that vedute started to flourish was closely connected with the rediscovery of the antiquity that begun with journeys of artists, architects, and archaeologists, and first studies conducted in the ancient Greece and Rome, as well as other cultures in northern Africa that were identified during the spectacular journey of Napoleon to Egypt in 1785.

European veduta painting was part of the education of young people in Great Britain adapted to other European countries and based on the Grand Tour program that enabled to learn about the world, its culture and history, broaden one's horizons, and exchange ideas and information.

In the 18th and 19th centuries, the veduta painting in Poland was developing on the one hand as part of and under the influence of European trends and on the other, due to heavily emphasized aspect of discovering and documenting great national past which was of a special importance after Poland lost independence and its statehood was eliminated by the partitioners (it became the carrier of patriotic content and the source of continuation of national consciousness and identity).

The last king of Poland, Stanislaw II Augustus, played an important part in this program. He established an artistic academy under his patronage, Academy of Fine Arts, and invited prominent artists (mostly Italians): a Venetian *vedutista* Bernardo Belotto (known also as Canaletto) and Marcello Bacciarelli whom he entrusted with the management of a smaller artistic school, the *Royal School of Painting*.

Most of the artists who trained there were portrait painters and miniaturists, e.g. Wincenty Fryderyk de Lesseur, Józef Kosiński, Józef Wall, and Zygmunt Vogel who was admitted to the Royal School of Painting when he was only 16. He was the one who was entrusted with the task of documenting ruined monuments of Małopolska (Fig. 2–4).

Polish veduta paintings:

Fig. 2. Ruins of castle in Janowiec by Zygmunt Vogel [10]   Fig. 3. Ruins of castle in Krasnystaw by Zygmunt Vogel [10]

Fig. 4. Ruins of castle in Ojców by Zygmunt Vogel [10]

According to Jerzy Banach, value of these works lies in the attention to the accurate portrayal of the building's state using strokes that are "softer and kind to the age and state of the monument" [1, p. 131]. He explicitly states that apart from the documentation, the main goal of the project was to promote national memorials and monuments which "was justified by the general ideological trends: drawings of 'ancient monuments' and tombstones… are an expression of the passion for learning about the national past that was common then" [1, p. 131].

2. Credibility of the Iconographic Sources from the 17th to 19th Centuries

When assessing the credibility of drawings as iconographic sources, it is important to pay attention to not only the talent and artistic sensitivity of the author but also to the quality of their method and their knowledge of rules of depicting space. The craft required of them not only the knowledge of geometry and perspective but also of new methods that were developed most notably in the Renaissance, as described by Andrzej Białkiewicz. He mentions that as far back as the beginning of the 16th century "…the idea of the distance point was defined for the first time and the rules of drawing from the lateral perspective were given…" [3, p. 28]. Moreover, he comments on the role of tools that were used increasingly more and more often since the times of Leonardo da Vinci: "…he experimented with camera obscura that was improved with mirrors, prisms, and lens and in the 18th century became a popular portable box used practically to create perspective drawings…" [3, p. 36].

In his thorough research on the 19th-century iconography of Kraków, Jerzy Banach noticed an obvious evolution of the quality of panoramas both in terms of the technique and technology of print that was improving over time. He also mentioned that early drawings are characterized by a certain awkwardness and objects have "thick outlines and lose details in the monotonous greyness…" [3, p. 19]. With time and changes in the style, the content of the drawings started to diversify.

Furthermore, Jerzy Banach characterizes the documentary value of the examined iconography. He considers as most valuable the works of Henryk Walter, François Stroobant, and Jan Głowacki, attributing the accuracy of their lithographies to the desire for rivaling the competition of the photography as well as to the diligent documentary methods based on the system of drawing sketches from nature.

Based on the above-mentioned views, one can assume that panoramic views of cities from the turn of the 16th and 17th centuries are of vital significance as a historical sources recording information important for scientific reconstruction.

The opinion of Maciej Bonawentura Pawlicki [7, pp. 161–174] contributes a lot to the assessment of the iconographic materials for the purposes of scientific works. He established that even though in many analytical publications views of cities from the turn of the 17th and 18th centuries are considered to be "of licentia pictorica nature" illustrators creating panoramas of the cities included in the treaties knew the principles of geometrical structures

very well and were capable of reconstructing and illustrating the topography accurately using contemporary techniques of measurement and leveling.

When presenting this view, M. Pawlicki invokes "an important work by Guarino Guarini from the 2nd part of the 17th century that lists the principles of complex geometrical structures, projection of planes on spheres, and using principles of leveling to present complex topographical relief" [7, p. 164]. This author's research is based on the conviction that the most popular method of verification of credibility of panoramas of cities consists in the comparative analysis using later cartographic maps from the turn of the 18th and 19th centuries and comparing them with sources while only thorough and expensive field investigations may broaden knowledge about the spatial development and assess the real cognitive value of views from the turn of the 17th and 18th centuries.

Maciej Bonawentura Pawlicki compared in his article the views of the examined cities, Zamość (panorama printed in G. Braun's work from 1618), Warszawa, and Poznań, and their geometrical structures (using collineation[1]) with their actual layouts. This enabled him to reach an important conclusion concerning the cognitive value of the views which "were depicted using the established graphical norms and distorted according to the logic motivated by the principles of geometrical abstraction" [7, p. 173].

3. Geodesy and Cartography – Ancient Times and Antiquity

Geodesy (from the Ancient Greek word *geodaisia*: *ge* – Earth and *daiein* – to divide) began in the 3000–5000 BC as proven by the existence of surveying guidebooks in ancient Egypt and institutions that conducted surveys and created maps in China.

Geodesy and cartography were known and widely used in the ancient times when planning out and creating monumental layouts of palaces, temple grounds, cities, or even settlements for craftsmen building tombs and pyramids for pharaohs.

Without knowledge of principles of geodesy and cartography, it would be impossible to plan out, chart, and erect the greatest cities of the ancient world such as the Egyptian Memphis (with 30 thousand inhabitants in 3100 BC), Babylonian Ur (in 2030 BC it was the biggest city in the world with about 65 thousand inhabitants and the surface area of 50 hectares), or the capital city of Thebes (with 70 to 80 thousand inhabitants in the first half of the 3rd century BC). Plans of these ancient cities have regular, geometrical layouts of streets and squares as well as individual city blocks and prove that an accurate cadastral limitations were used.

Apart from geodesy, the methods of mapping terrain, natural topographic structures, and structures erected by humans were also being developed.

There is a spectacular evidence in support of this claim in the form of the oldest known map that was discovered in Iraq and carved into a clay tablet (Fig. 5, 6), originating in the Acadian city of Gasur. Dated to the period between the 24th and the 22nd centuries BC, it is

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[1]   Not of documentary value.

a garden plan. The map includes a layout of the adjacent mountains, rivers, and cities. Even the directions of the world are marked [8].

A clay tablet from Gasur with the map of terrain and its topography:

Fig. 5. original in a preserved state [8]   Fig. 6. graphic reconstruction of the drawing and
                                                                          its content [8]
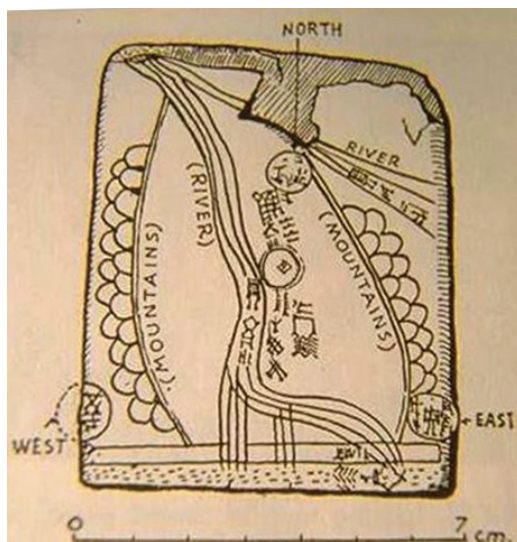
The above-mentioned find leads to the question about the tools used during the surveying and creation of plans and maps based on the surveys from nature.

It turns out that the the so-called Mynas Codex of the National Library of France, i.e. a collection of various texts and treaties created by ancient copyists, confirms the existence of such tools.

The collection includes the description of diopter (Fig. 7), a surveying tool dated to the 3rd century BC. Thanks to the descriptions, the scientists were able to reconstruct it (Fig. 8).

The development of geodesy in Ancient Rome was connected not only with the urbanization but also with the administration and investments in the far-reaching areas of the Empire. It is a well-known fact that during the reign of Augustus, in the Empire there were professional corporations of surveyors as well as schools teaching applied geometry and law. Gromatici[2] or agrimensores used simple but efficient surveying tools, including the so-called Groma[3]. This instrument was used to map out the axes of main streets in Roman cities (cardo and decumano), roads, and aqueducts.

Historians of European urban planning are certain that in the early Middle Ages, in times of an extraordinary development of cities [2], of fundamental value were an excellent knowledge of topography and an ability to locate in in a planned composition and its parts.

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[2]   Association of surveyors in the times of Ancient Rome.
[3]   A surveying tool consisting of a vertical tripod sinking in the ground and a bracket on which a rotary cross with arms at right angle was installed together with a device with a set of risers for setting horizontal position.

Fig. 7. A sheet with the description of the diopter [5]
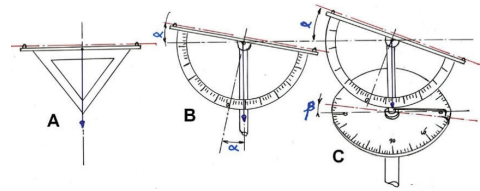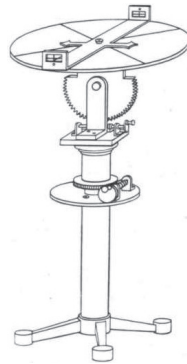
Fig. 8. The reconstructed model and evolution of the theodolite over time [9]

According to Tadeusz Tołwiński, "space surrounded with city walls was mapped out according to the estimated size of the city. Initially, medieval towns has several thousand of inhabitants. Later, this number increased to a dozen or so to several dozen of inhabitants... City walls were marked with certain reserve so that free space would remain behind the constructed residential blocks for some time that was used for farming or as market places" [12, p. 66]. He believes that the builders of such units had significant knowledge, abilities, and imagination.

Even if the Middle Ages had no spectacular discoveries and inventions, knowledge about city building was still extensive and based on the traditions of ancient architecture[4] [13, p. 112]. It is important that *The Ten Books on Architecture* by Vitruvius were discovered only in 1415 in the library of Saint Gall Abbey. Thus, one can assume that he might have been a well-known builder of cathedrals and knowledge included in his books had impact on the construction of such monuments as cathedrals in Chartres, Amiens, or Paris.

The development of cartography was a result of great geographical discoveries at the turn of the 15th and 16th centuries made by such people as Marco Polo, Christopher Columbus, and Vasco da Gama. They resulted in the introduction of such instruments as: *polimetrum* (for the measurement of vertical and horizontal angles), *theodolitus*[5], or an instrument constructed in the second part of the 16th century that was the closest to the modern theodolite (equipped with a compass and set on a tripod).

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[4]   The author believes that "very often the builders of cathedrals and churches had impact on the urban development of the entire city; contracts signed with the district reveal that they were often obligated to build defensive walls, fortified gateways, wells, and towers; thus, they were the true builders of the cities. Among them one can find the most outstanding architects of these times: Arnolfo di Cambio and Giotto in Florence, Maitani in Orvoieto, and others".

[5]   A measuring instrument created by Jan Pieterszoon Dou (1573–1635) with two pairs of sight vanes set on a alidade.

Inventions connected with new printing methods (especially the development of typography, i.e. copying images and text in large quantities) supported the spread of cartography, especially in view of the needs created by the administrative management of one's own territories, development of international political and economic contacts, and an increasing social mobility.

The oldest system of copying images or pint multiple times was a technique of *estampage*[6] used in China. In the 8th and 9th centuries, the Chinese widely used woodblock printing that later spread in Europe in the 14th century. It was used to create not only illustrated books but also calendars and maps used more and more often in sailing and travels.

Wood engraving was gradually replaced with lead, tin, and copper plates. Since the first half of the 15th century, the copperplate (engraving on copper) had been used to create matrices of cities and maps of European countries or regions.

Lucyna Szaniawska writes about that when she analyzes the beginnings of European print cartography using woodcut and copperplate blocks [11, pp. 283–306]. Analyzing both the technique of execution and content included in the plans, she comes to a conclusion that the copperplate enabled to transfer more detailed geographical information, was more durable than woodcut and suitable for fast update of information. Furthermore, it enabled to increase the number of details in the drawing. Thus, cartographic works from the turn of the 16th and 17th centuries had high artistic quality invaluable informative value: "work of two craftsmen George Braun and Frans Hogenberg entitled Civitates orbis terrarum that was published in Cologne between 1572 and 1617 from the very first volume was full of plans and panoramas of cities that were rich in content and saturated with strokes" [11, p. 292].

However, not only the development of cartographic techniques and the improvement of geodetic tools caused the steady increase in the accuracy of geographic maps (their density and attention to detail) but also the requirements of new recipients, more and more often national authorities responsible for efficient administration and management of the given area [11, p. 292].

4. Geodesy and Cartography in Poland

In Poland of the Piasts, the need for efficient administration of the territories undergoing merger as well as for the development of urban settlement was the reason for creating royal "geodetic services". According to historians' research, this was the role of prince's and royal *zerdnicy*[7] who are mentioned in texts from the 12th and 13th centuries [4].

With time, *zerdnicy* would transform into royal chamberlains (position created at the end of the 13th century) and manage state treasury. This was the beginning of the territorial authorities appointed to decide in border disputes, estimate value of real estates, and

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[6]   Technique of copying images used in China during the reign of Tang dynasty that consisted in carving in stone or bronze and making impressions on paper.

[7]   Polish word *zerdnik* is derived from the surveying activity done with simple tools: poles (in Polish: *zerdz*), sticks, and ropes. They measured land on site and demarcated city boundaries.
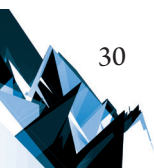
classify lands. At the end of the 14th century, chamberlains transformed into a self-governing institution of the gentry.

A significant agricultural reform[8] was implemented in the medieval Poland and a sudden increase in the settlement and planting of numerous towns led to the demand for qualified surveyors. Thus, in the 15th century the University of Kraków with the first Polish Geodesy Department started to train geodetic surveyors.

The beginnings of Polish cartography are connected with the dispute between the Order of Teutonic Knights and Poland and the need for documenting affiliation of lands to the Republic of Poland. Two maps from 1450 have been preserved: lands of the Teutonic Knights and lands of Pomorze Gdańskie. They were prepared for the presentation in the Holy See.

In 1491 plans of Central Europe were published in Poland by cardinal Mikolaj of Kuza and in 1507 Bernard Wapowski, astronomer and prominent Polish cartographer, worked with Marco Beneventano on the Roman edition of *Geographia Klaudiusza Ptolemeusza* atlas that included maps of Polonia, Lithuania, and Russia.

Contribution of another Pole, Wacław Grodecki, was recorded in 1570 in the form of preparation of the map of Poland for a famous European publishing house, a systematized collection of world maps, *Theatrum orbis terrarum*, prepared by Abraham Ortelius.

5. Conclusions

When analyzing cartographic works and landscape painting from the 17th and 18th centuries in the context of a dynamic development of the world, one cannot omit their important contribution to the scientific reconstruction of ruined, devastated, or significantly transformed units/complexes of buildings.

Progress in numerous fields of knowledge such as geodesy, mathematics, astronomy, and geometry and many geographical discoveries of these times and progress in navigation connected with them as well as the development of techniques of recording and copying images, translated directly into the quality of work of cartographers and artists who wanted to catch up with the rapidly changing world and specialized in their lines of work and thus, became documentarians in the context of their contemporary realities.

Thus, one cannot avoid an attempt at recreating a previous appearance of individual objects or even complexes without taking into consideration their views and silhouettes immortalized in the iconography depicting the past.

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[8]   As a result of this reform, land was surveyed and divided into Polish units of *lan* (about 16.8 ha) and rents in kind were changed to cash benefits.

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Oleg Sleptsov orcid.org/0000-0001-5441-5453
o.sleptsov@me.com

Margaryta Yakovenko orcid.org/0000-0002-1080-3443
kumee4ka@gmail.com
    Department of Technical Fundamentals of Architecture Design, Kyiv National
    University of Construction and Architecture

Role of the Department of Architecture Fundamentals and Architectural Design of Kyiv National University of Construction and Architecture in shaping the Kyiv architectural school

Rola Katedry Podstaw Architektury i Projektowania Architektonicznego Kijowskiego Narodowego Uniwersytetu Budownictwa i Architektury w tworzeniu kijowskiej szkoły architektonicznej

Abstract

The article is focused on identifying the role of the Department of Architecture Fundamentals and Architectural Design in shaping the architectural school of Kyiv National University of Construction and Architecture (KNUCA) as part of the Kyiv architectural school. It is performed by applying the deductive method, i.e. consistent analysis and study ranging from Kyiv architectural school elements. The article provides analysis of the key historic landmarks of its development, its fundamental principles, determined for the first time, methodological approaches, and prospects of development. Having undertaken the analysis, KNUCA was found to be playing a prominent role as a leader in methodology of training architects.

Keywords: architectural school, Kyiv National University of Construction and Architecture, historical landmarks, methodological fundamentals, graduates, scientific and creative achievements

Streszczenie

Głównym celem tego artykułu jest określenie roli Katedry Podstaw Architektury i Projektowania Architektonicznego w tworzeniu szkoły architektonicznej Kijowskiego Narodowego Uniwersytetu Budownictwa i Architektury w kontekście szkoły architektonicznej w Kijowie. W tym celu zastosowano dedukcyjną metodę polegającą na sekwencyjnym ruchu analizy i badania elementu kijowskiej szkoły architektonicznej. Pod uwagę brano główne historyczne etapy formacji, po raz pierwszy zdefiniowano podstawowe zasady metodyczne i perspektywy departamentu. Przeprowadzone badania udowodniły, że KNUCA jest liderem w dziedzinie metodologii nauczania na liście miejsc kształcących przyszłych architeków.

Słowa kluczowe: szkoła architektoniczna, Kijowski Narodowy Uniwersytet Budownictwa i Architektury, historyczne kamienie milowe, zasady metodyczne, absolwenci, osiągnięcia naukowe i twórcze.

1. Introduction

Term "architectural school" is mainly used in the meaning of a specific educational institution. This is a special concept different from semantically similar definitions of "scientific schools" and "art school". The architectural school stands out among other training institutions, since in its work it combines elements of scientific and art schools. This stems from the very nature of architecture, as high quality architecture is impossible without scientific knowledge in geometry, structural mechanics, fundamentals of structures, and artistic skills – the ability to express the idea using artistic means. Thus, we can say that the architectural school is a cultural phenomenon that was developed and shaped at a specific historical period and is characterized by prominent architectural artistic ideas, tectonic accuracy and commonality of artistic paradigm of school representatives.

Natalia Kondel-Perminova in her dissertation "The role of educational institutions in the development of architecture and urban construction in Ukraine: end of 19th-early 20th century" [6] analysed the work of educational institutions in Ukraine, given the historical evolution of the construction profession and the profession of architect, looked into social, economic, cultural and historic prerequisites for architectural and construction educational institutions to appear in Ukraine and the stages of their development. She determined content and training methods in Ukrainian educational institutions at different stages in these time spans. She established the nature of the interconnection that gradually developed between educational institutions and professional internship. Yuliana Petrovska's thesis "The interconnection of architecture and art in the Lviv architectural school's development" [4] and Natalia Horojan's "Kharkiv architectural school at the time of its establishment and development: end of 19th– early 20th century" [8] respectively examined the establishment, shaping and development of Lviv and Kharkiv architectural schools. Kyiv National University of Construction and Architecture (KNUCA) and its influence on the establishment and development of architecture in Ukraine was not the subject of these studies, though. Oleksandr Kaschenko, dean of the Department of Architecture, KNUCA, examines the issues of training architects in Ukraine in a number of scientific articles. However, the role of the Department of Architecture Fundamentals (AF) and Architectural Design (AD) in the shaping of Kyiv architectural school has not been researched yet.

Leading architectural and design schools in Ukraine and the CIS can be best identified when reviewing the results of annual International Competitions of the best diploma projects and works in the architecture, design and artistic professions. For many years, top of the list as to the number of international awards, certificates and diplomas at the competition has been reached by Kyiv National University of Construction and Architecture, Kharkiv National University of Construction and Design, National University – Lviv Politechnika, National Academy of Fine Arts and Architecture, National Aviation University and others.

2. Formation, fundamental principles and methodological approaches

Using the method of systematization, the main historical landmarks of the Department's formation were identified, for which archival data and literary sources were used [3].

In 1930, the continuous hereditary line of the Faculty of Architecture and the present Kyiv National University of Construction and Architecture began as a promising integral institution.

From 1939 until Ukraine acquired its independence it was called the Kyiv Civil Engineering Institute (KCEI). The Department of Architecture Fundamentals and Architectural Design has been an integral part of the Department of Architecture since 1964. It was established by breaking away from the Department of Architectural Designing and was initially called the Department of Interior, Furniture and House Devices. Until 1969, the Department was headed by Oleg Sveshnikov. At that time, in addition to in-depth study of new specializations, the faculty taught fundamental subjects on the typology of housing, designing residential buildings, introduction to specialization, and history of art and architecture. The faculty members were actively involved in scientific research, with many lecturers defending their PhDs.

In 1969 the Department was headed by Victor Savchenko, a KCEI graduate of 1950, Doctor of architecture (1983), Professor, Honorary Architect of the USSR (1985). In 1972, the department changed its name into Fundamentals of Architecture and underwent reorganization. There was a postgraduate course at the department. In 1982 the department faculty was actively involved in constructing and designing a new building of the department and today the building of the architectural department remains the only national example of a single specialized university campus for architects.

In addition to teaching specialization, interior and reconstruction, the faculty provided instruction on fundamental subjects on the typology of housing, designing residential buildings, introduction to specialization, and the history of art and architecture. The faculty were actively involved in scientific research. The experimental design laboratory played a prominent role at the Department: it was here that the scientific accomplishments and methodological projects of the Department were developed, tested and implemented.

It was a time when new educational approaches were employed in teaching key architectural subjects: Sociology of architecture, Psychology of perception of architectural constructions, Fundamentals of architectural composition, Synthesis of arts in architecture, etc. There was a postgraduate course at the department, lecturers and professors were actively involved in scientific research.

This period was the time of formation of the scientific school of the faculty of architecture, and leading departments, from the 1960s, began to form distinctive and vibrant research centres. Such a centre, significant for education and architecture in Ukraine, the Department of Architecture is included in the controversial 1980s.

In 1987 Valentyn Yezhov, a KCEI graduate from 1949, Doctor of architecture (1983), Professor (1990), People's Architect of Ukraine (1999), author of numerous projects, was elected the head of the Department and the Department's name was changed again into Department of Architecture Fundamentals and Architectural Design.

By that time, the Department had already become a leading one at the architectural department, teaching specialised courses (History and theory of interiors, Accessories and fitting material, Furniture and devices in interior, Psychology of architectural perception, Fundamentals of typological analysis: History and theory of reconstruction and restoration, Urban aspects of reconstruction, Reconstruction and new construction in historic environment residential and public houses etc.) for senior students, as well as lectures delivered on architectural education – Theory of architectural composition; Introduction to specialization; Fundamentals of architectural designing; History of architecture: Architecture of ancient world, History of architecture of Middle Ages and Early Modern Period, Modern national (Soviet) architecture, Modern world architecture, History of art, History of urban planning, History of Russian architecture, History of architecture of Asian, African and Latin American countries, and a Regional architecture-practical course introduced by Viktor Chepelyk in 1998. The principle of inheritance in lectures from the History of Ukrainian architecture was clearly traced (initiated by Victor Chepelyk in 1988 coauthored with Associate Professor Volodymyr Zabolotniy in 1990–1999) [2].

This period of activity of the Department also unfolded during the turbulent historical events in Ukraine, when all spheres of life were subjected to complex tests and entered a state of rethinking the basics and guidelines. The complexities of politics, economics, architecture and construction have combined with a systemic renewal and the beginning of a difficult integration into the European space of education and science. And, as before, in the difficult and decisive nineties, again it was necessary to preserve the reproduction of knowledge and training of new teachers and scientists. The head consistently implemented the idea of training, on the basis of graduate school, a group of promising scientists who, learning from professors' teaching, organically become their followers. This group has preserved its integrity and became the basis of the Department staff today.

In 2010 the Department was headed by Oleg Sleptsov, the KCEI graduate of 1980, Doctor of architecture (1999), Professor (2002), Honorary Architect of Ukraine, laureate of State Award of Ukraine in Architecture (2000), member of the National Association of Architects, member of the Ukrainian Academy of Architecture (2000), author of numerous urban centres, buildings, and constructions in Ukraine and abroad.

With the help of the method of comparative analysis all the departments of the faculty of architecture were analysed. The Department of Architecture Fundamentals and Architectural Design is multidisciplinary and is the largest at the Faculty of Architecture. In the 2018–2019 academic year, the Department employs doctors and candidates in architecture – 34 teachers, including: professors – 10, associate professors – 16, senior lecturer – 1, assistants – 7. Teachers of the Department are involved in teaching 55 disciplines. At the same time, other departments have no more than 25 teachers in their composition.

In 2017–2018, there are 14 postgraduate students at the Department. Since 2010, 3 Doctor's dissertations and 16 PhD dissertations have been defended. Over the past 25 years, about 45 Doctor's and PhD dissertations have been defended.

Recently, the Department of Architecture Fundamentals and Architectural Design was joined by Valentyn Shtolko, People's architect of Ukraine, President of the Ukrainian Academy

of Architecture, member of the International Academy of Architecture, laureate of the State Award of the USSR, laureate of the State Award in Science and Technology, twice laureate of the State Award of Ukraine in Architecture; Yuriy Serogin, Distinguished architect of Ukraine, member of the National Association of Architects, corresponding member of the Ukrainian Academy of Architecture, twice laureate of the State Award of Ukraine in Architecture; Yanosh Vig, Distinguished architect of Ukraine, member of the Ukrainian National Association of Architects, member of the Ukrainian Academy of Architecture, laureate of the State Award of Ukraine in Architecture.

In 2017, the Department launched a programme of international scientific and methodological cooperation with the Faculty of Architecture of Harbin Polytechnic University (Harbin, China).

Groups of students of the Department, uniting in teams with design students and other departments regularly receive the highest prizes in the prestigious National architectural student competition "Steel Freedom".

Since 2018, students of the Department have been taking part in the program of architectural double degree, performing two parallel theses in KNUCA and Lublin Polytechnic during training at 5 and 6 courses. This is the principle of integration with educational institutions in other countries.

Using the interview method, graduates of the Department were interviewed [7]. On the basis of their answers to the question of the questionnaire, another principle of development of the architectural school of KNUCA was formed – the principle of innovation. Time does not stand still and today new technologies are used, but the academic approach to training architects in KNUCA makes it different from the system of training abroad. Its advantage, though, is the artistic element maintained by KNUCA as a prominent element in the architectural school. So, during the first year of study the focus remains on academic training to prepare students for creative designing, developing their ability to graphically represent measurements, drafting architectural buildings, orders and their details, teaching method of drawing (mono- and polychromic). The students, therefore, can acquire the taste for their future profession by doing practical assignments, mastering knowledge about landmark architectural objects, developing skills to enable light/shadow modelling of architectural forms, and developing spatial thinking.

3. Prospects of development

It keeps expanding by adding new specializations for masters in educational and scientific programmes and masters in educational and professional programmes, namely: specialization Architecture of Buildings and Constructions: reconstruction and restauration of architectural objects, Architecture of Buildings and Constructions: sacral architecture, Architecture of Buildings and Constructions: innovative architecture. This renewal and expansion of specializations started in 2017. New curricula and relevant disciplines have been developed. Of particular importance nationwide is specialized training in the field of sacred architecture,

along with general reconstruction and restoration, as it is developed and implemented for the first time in Ukraine.

KNUCA graduates and their works and creative input are a sign of quality of training at the higher educational institution. Among KNUCA graduates there are laurates of the Stalin Award, the State Award of the USSR, the State Award of the Ukrainian SSR named after Shevchenko, the Lenin Komsomol Award in Architecture, public officials, scholars, and architects with major accomplishments in other areas as well [5].
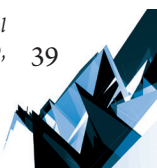
Given the identified specificities of its development, the Department has developed methods of improving architectural schoolwork and its prospects. KNUCA's model of architectural education for the future is primarily a student-centered approach that was developed in 2015 at the European conference "Education in European countries". Secondly, developing the essence of architectural education: flexible educational syllabi; democratization of the educational process to meet the needs of modern society; its universal nature linked to the resolution of social, scientific, technical, architectural, and environmental challenges taking into consideration the artistic and aesthetic aspects. We have already embarked on this path and the first steps made here are the introduction of selective courses that students are entitled to, provided they have a clear idea as to the goals they are pursuing.

4. Summary

On the basis of the three specific principles of development of the architectural school of KNUCA: the principle of continuity, the principle of innovation, and the principle of integration, it can be concluded that KNUCA plays a crucial role in developing the methodology of training architects in Ukraine. Historically, it is here that a scientific and pedagogical school has developed which has a significant impact on the establishment and development of architectural education at the university level in Ukraine. In the course of development of architectural education in Ukraine, KNUCA represented Ukraine in the central educational methodological union. KNUCA serves as the basis for scientific and methodological commissions on architectural education at the Ministry of Education and Science of Ukraine. That is why it is here where fundamental syllabi are developed that serve as the standard to be disseminated to other departments of higher educational institutions in Ukraine. Other departments in their turn add variable elements to them. KNUCA representatives are permanent members of accreditation commissions and define licensing standards in the regions. KNUCA has the strongest faculty of high potential that plays a crucial role in the philosophy of architectural education in Ukraine, its policy and strategy.

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Ewa Węcławowicz-Gyurkovich 🆔 orcid.org/0000-0003-3920-445X
ewa.weclawowicz-gyurkovich@pk.edu.pl
   Institute of History of Architecture and Monuments Preservation, Faculty
   of Architecture, Cracow University of Technology

Intense colours in the latest works of architecture

Intensywne kolory w architekturze najnowszej

Abstract

Vivid colours in external views of the latest works of architecture are not commonplace. Le Corbusier introduced basic colours delicately, on small fragments. Architects inspired by his work most often select rather small fragments, marking with only a single colour that is clearly contrasted with the entire composition. The construction of massings with vivid colours is the domain of either young and bold or experienced architects who can convince decision-makers about their proposals and rationale. The author presents structures with elements of various colours, as well as single-colour structures that feature surprisingly striking colours, completed by outstanding contemporary architects.

Keywords: contemporary architecture, stararchitects, colour in architecture

Streszczenie

Ostre kolory na zewnętrznych ścianach budowli architektury najnowszej nie występują często. Le Corbusier delikatnie wprowadzał na małych kawałkach kolory podstawowe. Inspirowani jego twórczością architekci wybierają raczej niewielkie fragmenty powierzchni, używając najczęściej tylko jednego koloru skontrastowanego wyraźnie z całą kompozycją. Budowanie brył o mocnych żywych kolorach jest domeną młodych odważnych architektów lub tych doświadczonych, którzy potrafią przekonać decydentów do swoich wyobrażeń i racji. Autorka przedstawia obiekty z elementami różnych kolorów, a także jednobarwne o zaskakujących mocnych barwach, realizowane przez wybitnych współczesnych architektów.

Słowa kluczowe: architektura współczesna, stararchitekci, kolor w architekturze

1. Introduction

In the latest architectural solutions, vivid colours appear extremely rarely. The colours of natural contemporary construction materials clearly dominate: grey concrete, metal with its grey hues or rusty corten, glass – either translucent or frosted, at times featuring pastel shades – stone, ceramics, timber in different tones of beige and brown. Sometimes only a small fragment of a building is accentuated with a stronger colour.

2. Colour in the work of Le Corbusier

Such was the case with the Unité d'Habitation in Marseilles that Le Corbusier designed at the start of the 1950's. Interest in the construction of a housing block of then-unprecedented scale, with a finish from a new material – cast concrete – with a mixed residential and service form of use, was immense. Over the course of the 18 months preceding the completion of its construction in 1952, as many as one hundred thousand people visited the building, each paying a 150 francs entry fee. When, after many weeks of absence at the construction site, caused by his travels to distant places, the designer finally returned to Marseilles to oversee the construction of the seventeen-storey block for 1,600 residents, he was surprised by the poor quality finishes of the concrete elements of cast walls on the building's loggias. Corbusier – who was also a painter – decided to paint the flat internal walls of balconies and loggias in a set of colours. These were vivid basic colours: red, yellow, blue and green, as only they were able to cover the unevenness of the walls [1]. Charles Jencks in turn pointed out that the introduction of colours on the loggias of the facade of the Unité d'Habitation was a result of an error in the design of window divisions, one that the designer had missed at his studio. The task of the various colours was to break up the monotony of the window layout, as well as to make the enormous scale of the building appear smaller. In this manner, Le Corbusier turned these errors to his benefit, as well as that of the building [5]. Explaining the principles of the design of the external facades of the Unité d'Habitation to his opponents and critics, Le Corbusier wrote that he had decided to create beauty through contrast. That he would conduct a dialogue between austerity and delicateness, between the bland and the vivid, between precision and chance. He wrote he would force people to think and to reflect; that it had been the cause for which he had designed the bold, flashy, triumphant polychromes of the facades [6]. This form of decorating the external facades was repeated in other of Le Corbusier's multi-family buildings – in Rezé les Nantes (1955), in Berlin (1958), Briey--en-Fôret (1961), as well as in Meaux and Firminy (1968). The colourful plaques under the windows (red, blue and yellow) appeared on the frontal facade in the Parisian Salvation Army Hostel, completed by Le Corbusier in 1933. Individual walls in striking colours can also be encountered in the interiors of the luxury Villa Savoye in Poissy (1931), or in the model semi--detached building in Stuttgart, at the model modernist housing estate of Weissenhof (1927)[1] [2].

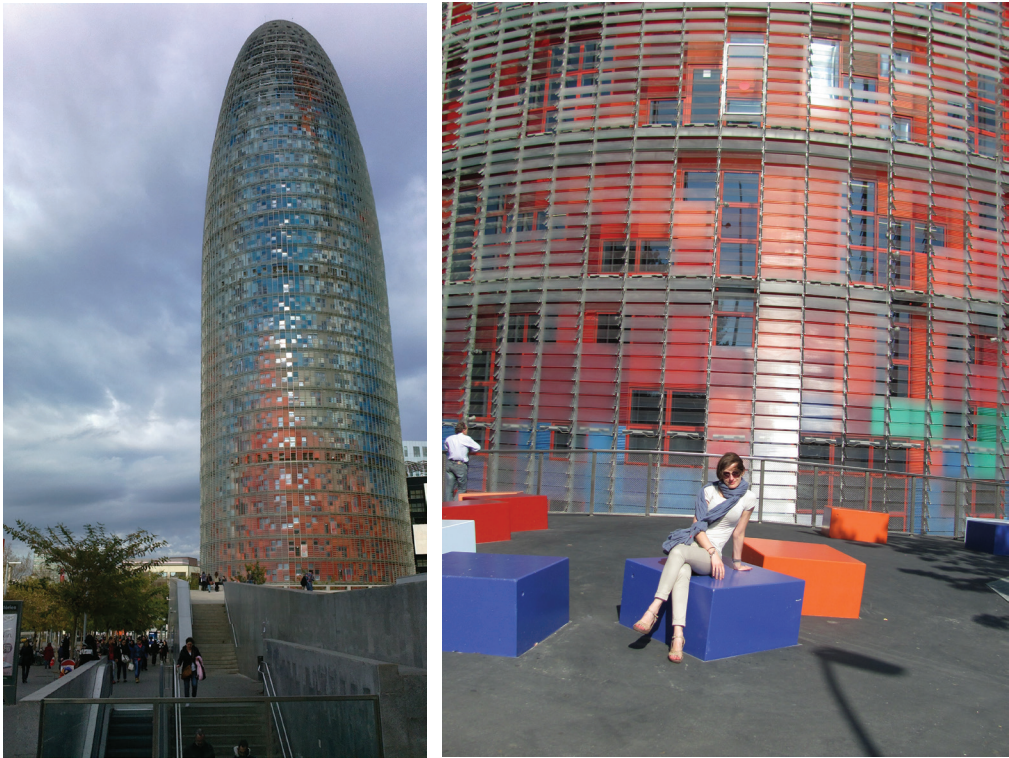[1] A subject of the author's *in situ* studies in the years 1992, 2001, 2003.

Fig. 1–2. Barcelona Torre Agbar, arch. J. Nouvel 2005, photos by M. Gyurkovich

In the last exhibition pavilion by Le Corbusier in Zurich (1963–1967), the architect changed the construction material that he had used since the beginning of his professional career. Instead of heavy concrete forms, a light metal structure appeared here, and thin coloured cladding was covered with porcelain enamel and used as a finishing material for the facades. The flat rectangular shapes introduced there were red, yellow, green, as well as white and black, in contrast to the large translucent glazing and grey structural elements. Charles Jencks wrote of this structure, built by Heidi Weber, confirming an inspiration with marine form that was common in modernism and particularly in the case of Le Corbusier. This nautical imagination and fascination with transatlantic liners can be seen in the entire building, including in its interiors. Jencks wrote that the external brightly painted panels that changed as colourful signalling flags, completed the metaphors and that all it took was to switch the surrounding green to blue to see an unusual ship cutting across the waves [6].

3. The latest completed projects from the start of the twenty-first century

The impact of the work of the father of modernism, the Great Corbu, on the subsequent generations of architects was significant. In the tall, neo-expressionist residential building built in 1999 in Paris at the intersection of Pavillons and Pelleport streets, the French architect
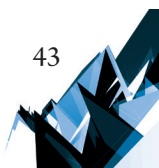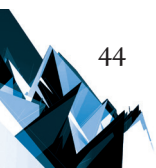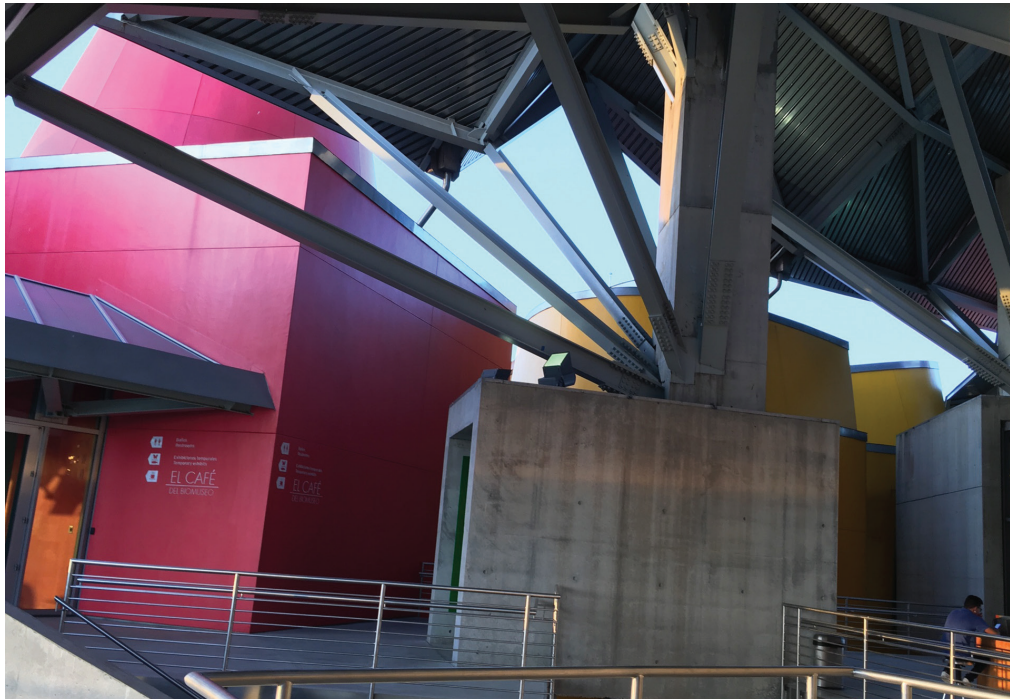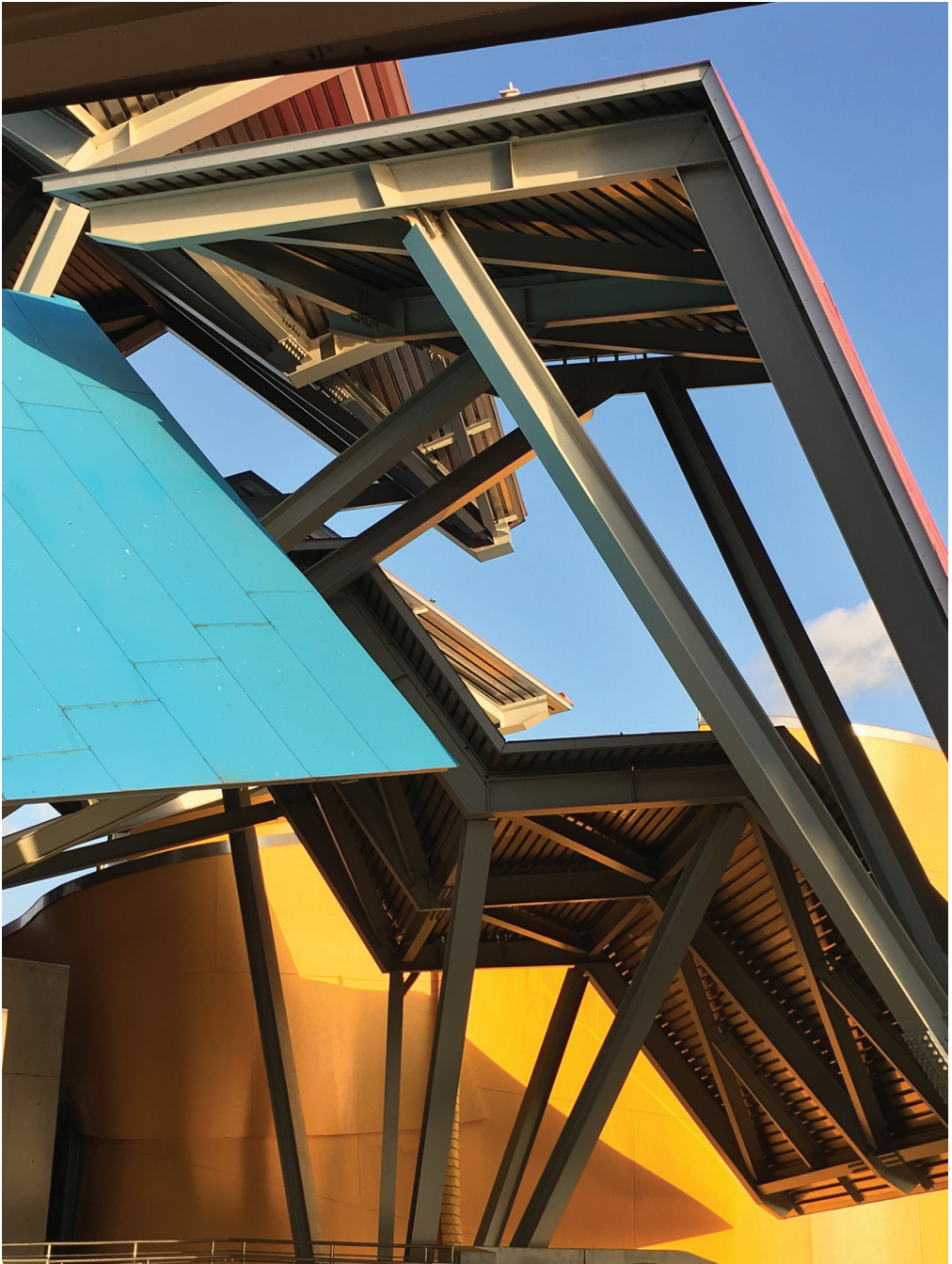
Fig. 3–7. Panama, Biomuseum, arch. F.O. Gehry 2014, photos by P. Górecka
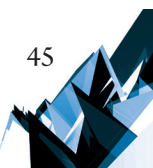
Frédéric Borel, inspired by, among other things, the work of Le Corbusier, introduced striking reds, yellows and blues in the building's fragments[2] [12]. The townhouse, with a complex massing composed of numerous elements, is intriguing and elegant, and we can find in it the qualities of painterly lyricism and spatial poetics[3]. Borel, by dividing and breaking up a section of the new townhouses in Paris into smaller pieces, represented his creative philosophy, in which he goes against and opposes the artificial principles of rationalism [13].

We can also find the somewhat demonstrative introduction of new structural and installation elements in the high-tech style, with striking, often surprising colours in the works of Richard Rogers from various periods. This is what the architect said in an interview years before: "I don't understand why everyone has to wear black, grey, and white" [17]. In an adaptation of the historical Las Arenas nineteenth-century bullfighting arena (2000–2011), located in the northern part of Plaça d'Espana, into a new shopping centre and mixed-use complex in Barcelona, the new primary structural elements were painted a vivid yellow colour. All the steel and reinforced concrete elements that were new were distinguished from the existing, historical ones. The employed colour contrast sometimes surprises us, just as metal pipes of air intakes, painted purple, placed in rich details and window openings of existing outer facades. The project took over 10 years to complete, as the Rogers Stirk Harbour + Partners team of architects decided to preserve only the external shell of the structure from the 1870's, maintained in the decorative Moorish Revival style [14, 15]. The walls, made of red clinker brick, with a large amount of bright stone details, were raised above by an entire storey, which became the new ground floor, supporting it on steel V-shaped columns, which were painted in a striking red colour. The metal supports bent into the shape of boomerangs and placed on the roof were painted red as well, upholding a dome with a span of 76 m, which covers the entire massing along with its surrounding observation deck on the uppermost storey. However, the oval marble hall placed in the centre, spanning 100 m, reminds us of the previous function of the building [4].

Of note is a completed project by Frank Gehry, the Puente de Vida Museum, opened on the 20th of March 2014 in the capital of Panama, located near Amador Causeway, commonly called the Biomuseum. This is Frank Gehry's first completed project in Latin America. The museum was placed at the mouth of the Panama Canal, where it enters the Pacific Ocean, on the grounds of a former US military base. It quickly became a hallmark of the city, creating, as the clients had wished it, a new and significant icon, similar to the Guggenheim Museum in Bilbao, Spain. The task of the museum is to present to the residents and visitors the object of the history, geography and biology of the Panama Canal and point their attention at the protection of the environment in this area. The foundation for the building's construction was built in 2001, however, due to its complicated steel structure, construction work was significantly delayed. The matter was not only about high financial costs, but primarily the construction capabilities of the Latin American country. The design team was obligated to simplify the structure and adapt its assembly to the technical skills

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[2]   A subject of the author's *in situ* studies in 2002.

[3]   Apart from an inspiration with the work of Le Corbusier, Wojciech Leśnikowski saw in this design a reference to a specific painting by Paul Cézanne – "Mont Sainte-Victoire" [13].

of local workers [19]. The museum's floor area is around 4,000 m². It was the architect's intention to create a new contemporary hallmark of the city based on an analysis of site--specific conditions. The new icon intrigues and invites tourists, in addition to bringing joy to residents. The introduction of multi-coloured roofs in striking intense colours appears to be a reflection of the atmosphere and mood of the architecture of the street of this part of the world. Vivid reds, yellows and orange colours, as well as blues or even greens, appear as if a gigantic bird of paradise has set down on the greenery surrounding the museum, on a narrow cape leading to the capital of Panama. According to the author of the article, this gathering of such a large number of simple, primarily gable roofs, which are sometimes superimposed upon one another and are suspended on different heights, can bring to mind the small towns or even settlements distinct of Latin or South America. Examples of such can include the small island of Santa Cruz del Islote in Colombia, created on a coral reef and sporting a surface area of 0.12 km², located at a distance of around 20 km from land and which was settled by African slaves. At present it features around 100 small houses which are home to over 1,200 people [20]. There is a complete lack of greenery and open areas, as this island is the most densely populated space on Earth – with one person per 8 m². However, the Biomuseum's roofs are not grey and rusted, but all are highly colourful. From the first conceptual sketches, Gehry assumed that the museum would be surrounded by a botanical park. The park's designer was Edwin von Gal. The broken roofs, continuing to a low height, appear as if they levitate, rising and falling, building gabled forms. At times we can observe a triangular cut-in near the edge of the roofs and in only one case the edge of a roof was finished with a soft, corrugated line. This multi-coloured steel canopy of roofs is supported by a complicated openwork steel structure.

An open, public atrium was created at the centre of the museum, from which one can enter eight independent galleries with varied layouts and thematic programmes. Spaces for permanent and temporary exhibitions were designed, as well as a shop with memorabilia and a café. Of note is the expansive and tall hall, in which a large number of concrete columns were placed and which have been cut off at various heights, their upper portions being slightly slanted, colliding, intersecting with each other, creating an atmosphere of restlessness, of planned chaos. In most spaces exhibits are shown in vertical, column-like cases, which are also fitted with colourful pastel shades. However, it is the interactive exhibits by Bruce Mau Design that are the most impressive. The museum shows the natural and historical evolution of Panama's origin, going back three million years in time. Two large aquariums show the Pacific Ocean and the Caribbean Sea which were separated by the Isthmus of Panama. The museum shows animals and birds from various periods, in addition to insects and microorganisms. An unforgettable impression is left by the suddenly appearing enormous images of tropical forests, lush greenery, tall waterfalls, footbridges and bridges suspended above chasms, the tied branches of tropical trees. Sometimes we also look at the world of nature, walking over glass surfaces. From the various levels of the museum there is an excellent view of the bay and the city's panorama. Interest in the project among residents of Panama and tourists alike was so great that it had been decided to open access to the building even before its completion.
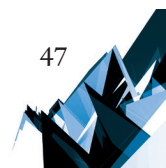
Colour had appeared earlier in Gehry's architecture, including in, among others, the Museum of Pop Culture in Seattle (1995–2005) where its freely sculpted, expressive massings were covered by colourful metal sheets of a golden, silver, blue and red colour [9]. J. Fiona Ragheb wrote the following of the inspiration with specific items and Jimi Hendrix's legacy in the construction of the building's massing. "The allusion to a shattered Fender Stratocaster is carried through in a glass sculpture that rides the crest of the building, suggesting the strings and frets of a guitar neck. The colours – a riot of gold, pale blue, purple, red, and silver – are symbolic references to various songs and events from the history of rock and roll, including Hendrix's song 'Purple Haze'..." [18]. The museum was devoted to the history of and study of popular music and science fiction. It features numerous mementoes from the period of fascination with rock and roll and gives the latest multimedia presentations at the highest level. Another time, in the hotel and Spa near the oldest wine shop in the area, Vinos Herederos del Marques de Riscal in Elciego, Basque Country, near Bilbao, Spain, Frank Gehry covered the building's restaurant and hotel administration buildings with interweaved and tangled belts of titanium sheets. The belts of metal sheets, which were imported from Japan, were used in three colours – silver and red, which was inspired by the colours of wine, while the third colour, golden, was the mesh in which the wines produced at this historical vineyard are packaged in [3]. However, the colours introduced in his sculpturally complex and expressive projects had never been as intensive and vivid as they were in the previously discussed Biomuseum in Panama.

Courage in the introduction of bold colours into newly built massings of the latest works of architecture surprises their audience. It is most often the domain of young, "bold" architects. This group undoubtedly includes the Frenchwoman Dominique Jakob and Brendan MacFarlane from New Zealand. They surprised the world with their projects of two buildings located in Lyon as a part of one of the largest post-port restoration projects in Europe, the Lyon Confluence, at the point of contact between the Rhône and the Saône rivers. The first of these is Le Cube Orange, an administrative building built in the years 2005–2010 at qua Rambaud Confluence [8]. The building surprises us not only with its large scale (29 x 33 m), but primarily with its bold orange colour. It was built as an extension of rather short concrete salt storage buildings from the start of the twentieth century. This bold colour is similar to the overalls or vests worn by road workers and has never appeared on the scale of an entire massing in architecture before. The concrete and glass massing was covered up to a height of six storeys with a dense aluminium mesh with rectangular modular openings, coloured orange, and in which small polygonal and oval-shaped openings were cut. The composition of the whole is accompanied by other surprises that had previously been beyond the imagination of its audience. It is an arched cut-away of the corner of the massing (up to around 1/3 of its height) at the ground floor, right near where it connects to the existing salt storage buildings, with dome-like tops of the three chambers, perhaps explaining the introduction of soft shapes into the cuboid, simple shape of the entire massing. Meanwhile, in the central part of the building, a surprising, gigantic oval hole was drilled, several storeys in height, with a small sphere placed inside – coloured orange, of course. Inside this opening, whose existence is hard to explain, we can see alternating horizontal belts of orange balustrades and their glazing, placed on
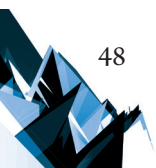
four of the building's storeys. The balconies located there can be used by the office building's employees for recreational breaks, during which they can observe the transformation of this post-port area with a surface of 155 ha. This surprising indentation reaches up to a third of the volume of the building. Furthermore, on the roof of this geometrical massing there is a deck allowing the employees of the two uppermost storeys to rest as well. Meanwhile a RBC gallery, in additional to a centre of the promotion and sale of contemporary dressing, have been placed on its lower storeys. Another of the building's values is its energy efficiency, which is a result of the introduction of double-skin facades, the installation of photovoltaic panels and a ground-source heat pump [16].

Four years later, in October 2015, the same area saw the opening of the second building – located directly on the Ranibaud shore of the Saône – the Euronews Headquarters, a television studio for international news channels, also designed by Jakob & MacFarlane [7]. This time, the architects introduced a vivid, bright green colour on the entire cuboid, horizontally stretched block, the colour resembling fresh May greenery, placed on a double aluminium sheet laid on top of the structure's glazed facades. Similarly as in La Cube Orange, two round openings were carved into the geometrical massing, as if resembling the lenses of cameras, which gather all the latest information to relay it to the audience. Others call these openings "eyes". They are also open towards the deck located on the roof [21]. The building features seven storeys and an additional underground level housing a garage. The decorative metal mesh visible on the outside of the facade can bring to mind associations with the fresh young leaves of spring plants, referring to the river and the wavy green areas located on the opposite shore of the Saône. The openings carved from the side of the river are smaller than in the neighbouring building, having a height of only three storeys. The author of these intricate openwork facades is Fabrice Hyber [22].

The French architect Jean Nouvel introduced intense, vivid colours into a number of his designs. 2005 saw the completion of Torre Agbar (now called Torre Glòries), an office tower of the municipal waterworks company, located at the intersection of Avinguda Diagonal and Badajoz de la Gloria square. The 144.4 m tall oval tower, inspired by the shape of a geyser, is visible from far away, towering above its surroundings. The reinforced concrete structure of the massing, with 4,400 window openings carved out of the concrete, has been covered with metal panels painted into 25 colours, ranging from red at the bottom to blues and the transparency of glass at the uppermost six storeys. The colours, introduced on small geometric rectangles, can bring to mind associations with fractal geometry or a gigantic spatial puzzle. The appearance of the entire massing being blurred was obtained by placing glass blinds on the outer wall, fastened to a steel structure. The horizontal narrow belts of either transparent or matte glass that forms this cover change their pitch automatically depending on sunlight[4].

Nouvel completed a multi-coloured building in the years 2001–2006 in Paris, right near the Eiffel Tower [7]. It is the Quai Branly Museum, featuring exhibits on the art of the civilisations of Africa, Asia and Oceania, as well as the Americas. The collections speak not only of the colonial past of France, but also that France is familiar with and respects other

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[4]   The author performed on-site studies in 2005 and 2008.

Fig. 8–11. Lyon, Cube d'Orange, arch. D. Jakob & B. MacFarlane 2010, photos by W. Kosiński

cultures. The main massing, red in colour and with a length of 220 m, has been raised up and is supported by columns. Apart from glazed elements, multi-coloured square or rectangular-shaped "boxes" extend outwards from it, housing lecture halls and exhibitions. This is what the architect said about the building: "…It's not Occidental building. For me it is a world dona with colors and shapes linked to an interpretation of Africa and Oceanic and American culture" [17].

The following two completed projects by Jean Nouvel were built in uniform colours, blue and navy blue, respectively. The Guthrie Tower was opened in 2006 on the shores of the Mississippi in Minneapolis, Minnesota, USA. The theatre was placed in an industrial area, against the background of existing silos and grain mills, therefore, in the glazed and metal, navy-blue massing we can find numerous elements inspired by its surroundings. They are the source of the oval shapes of the massing, the extended masts, the balcony that extends far towards the river, as well as other elements that reference industrial architecture. The

architect, by presenting the magic of theatre, wanted to tear down the borders of illusion and reality, displaying scenes from the life of the theatre on its external walls.

Three years later, in 2009, Jean Nouvel completed the concert hall of DR Byen, a Danish public radio and television broadcasting company, in Copenhagen. The structure is located in the district of Ørestad, where the architect could not find any element that he could form a reference to, which is why he decided to create a new, large-scale icon. The extensive main concert hall for 1,800 people was elevated 15 metres above the ground floor and placed on thin columns, practically suspending it on the strong outer structure. The massing, with facades composed of glass panels arranged on a diagonal grid pattern, was hidden up to the height of 45 m in a blue cuboid massing, covered in a transparent mesh. At night the mesh serves as a screen for multimedia visualisations. "...The architecture dematerialises, becomes a play of light and a synthesis of shapes, reflected off of the surface of the building..." – said the architect [23]. The structure, which has been dubbed the "meteor" by local residents, is occupied by a radio station and the national symphonic orchestra [11].

4. Colour in open public spaces

In recent years we have been able to observe the introduction of vivid colours at the level of squares, streets and pedestrian trail sequences that feature functions that are important to cities. In the Nørrebro district of Copenhagen, Denmark, a multi-cultural municipal park called SUPERKILEN was established (2009–2012), whose authors included the following teams: TOPOTEK1, BIG Bjarke Ingels Group and Superflex. The assumption of the design was to create an innovative urban space for an ethnically diverse community formed by 60 different nationalities. In order for the residents of this neglected and even dangerous district of Copenhagen to acclimatise and feel connected with their place of residence, it was proposed for each of the nationalities to place an object from their native country in this common space. This led to the formation of an urban garden with 108 elements, a "gallery of diversity". The lead designer of street furniture from the Danish BIG design team, Nanna Gyldholm Møller said that when her team had been invited to present the project in the neighbourhood, they had noticed that more had to be done than simply prepare an urban design. This community, its representatives from 60 countries and various nationalities, had been asked what were the best elements of street furniture from their countries [24]. Residents expect more than medium-sized and tall greenery or playgrounds for children from a modern park, also expecting spaces for practising sports, listening to music or carrying out various cultural projects. We can also work outside with a laptop here. The entire space, with a surface area of 30,000 m² and a length of 750 m was divided into three sections – the Red Square delineates a space for sports and recreation, the Black Square – is a small square with a fountain and benches around it, forming a sort of a centre of the entire complex, while the Green Park is meant for walking and rest. It is the red section that is different than in other cities and stands out, being used by residents of varying ages and with different professions and interests, similarly as the entirety of the park. This section is primarily meant for people

interested in sports with varying degrees of activity, e.g. like everyday running, volleyball or baseball, boxing, dancing in the air or riding the bicycle. The floor surface in the section meant for practising sports has been painted in a bright red colour, as well as in orange and various shades of pink. In some places there are geometric patterns built out of these colours, and sometimes the colour red extends to fragments of buildings or fills entire facades, and not only the single-storey ones, but also fills an entire windowless wall of a tall building that stands near this space. The red, orange and pink divan outlines the borders of the area meant for practicing sports. SUPERKILEN found itself in the final group of five projects selected for the prestigious Mies van der Rohe architectural award for 2013, which was an exception as it is an urban design. In 2013 the project also received the American Institute of Architecture award and was also nominated for the Red Dot by the Design Museum in London [26].

On a slightly smaller scale, yet in a location that is important to Dublin, the architect Maria Schwartz completed an extensive square in 2007. Called the Grand Canal, it is the main open public square in Ireland's capital, in the Docklands Development area. On the one hand, the space is open towards the Grand Canal, while on the other, its square is enclosed by the recently built new municipal theatre designed by Daniel Libeskind. From the north and south the square is surrounded by newly-built complexes of office buildings. Stone slabs form a sort of a red carpet on its surface that leads from the canal to the theatre. It is a diagonal belt that runs diagonally on the square's surface, clearly standing out from the grey of the surroundings and the green wedge located near the waterway. The red fragment of the layout features round vertical metal rods of a height varying between six to ten metres, which are slightly slanted in various directions. All of the rods, of which there is a total of 50, were lacquered in a bright red colour and placed in groups of several each on both sides of the dark red stone divan that stands out from the remaining parts of the surface of the square. The entirety of the composition is crossed by bright diagonal lines that supplement slight deconstructivist turns visible in the plan. It seems that the square prepares the audience for the restlessness and emotions that the visitors of Libseskind's theatre will experience inside its sculpturally complex and expressive interior [10].

The colour red, being the most visible, is commonly used in a carpet-like form on horizontal surfaces of squares and streets. Recently, a project was completed in St. Gallen, Switzerland, in which the open spaces of the city centre were covered with an almost literal red carpet. The Raiffeisen quarter was covered with a granulated latex carpet, similar to the soft surface of a sports pitch. The urban salon created in this manner was named Stadtlounge, its designers being the architect Carlos Martinez and the artist Pipilotti Rist. The project was built in two stages, between 2004 and 2011 [25]. Of note is the fact that, in order to provide comfort, this soft rubber surface covered not only the surface of streets and squares, but also all furniture, benches, seats, flowerpots, and even a car located in this 4,600 m² area. The space is meant solely for pedestrian traffic and the persons who work or have various errands to run in the surrounding buildings of this financial districts are provided with safety and a maximum of comfort [10].

In Europe, as well as around the world, we can encounter cities and towns in which the facades of buildings have been plastered or painted in various colours for centuries. Such was
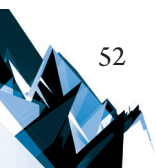
the case in the centres of historical European cities. On one of the 40 small islands of the Venetian Lagoon, Burano, famous for the production of delicate lace, the facades of buildings, doors and window frames have been painted in brightly coloured geometric patterns for years. The houses of Scandinavia or in Reykjavik, Iceland, also surprise us with bold colours. In the traditional Polish countryside, timber homes were painted blue when a maiden available for marriage resided in the home. Therefore there were some semantic codes in the selection of colour schemes, as well as fixed principles. Today architects rarely go as far as to introduce bold and vivid colours on entire buildings. They most often introduce a small colourful fragment that contrasts with the entire composition. The latest architectural solutions are dominated by natural colours in matters of facade finishes – the greys of concrete and steel, various shades of brown, resulting from the use of selected types of wood, toned down oranges and reds when using ceramics, rusty red metal sheets when using corten. The few examples shown above are but a small part of what we can presently encounter. It is good that they are few, as they clearly stand out against the background of white, grey and black – they scream, underscoring the significance of structures, most often bringing to mind painting and sculpture, which want to boldly go onto the streets of our cities. The use of bold colours in architecture and spaces that feature unique functions increases their impact strength and aids in the identification of places in the structure of urban tissue.

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Anna Rybak

Dawid Jankowski iD orcid.org/0000-0002-2013-0254
jankowski@indy.chemia.pk.edu.pl
    Chair of Chemical and Process Engineering, Faculty of Chemical Engineering
    and Technology, Cracow University of Technology

The hydrodynamics of a fluidised bed reactor

Hydrodynamika reaktora z warstwą fluidalną

Abstract

This article presents results concerning the hydrodynamics of a reactor with a porous fluidised bed (group D according to Geldart). Pressure drops were experimentally determined by gas flow through the bed and empty column. Using equations from literature flow resistance on the bed and gas distributor, critical velocity and terminal velocity were calculated and the obtained results were compared with experimental data. The equation which best described the work of the tested fluidised bed was identified through a process of trial and error. The influence of sieve being operated on pressure drops occurring during the process was determined and its applicability in the other conditions was verified.

Keywords: fluidisation, fluidised bed reactor, sieve plate, hydrodynamics

Streszczenie

W pracy zaprezentowano wyniki dotyczące hydrodynamiki reaktora z porolitową warstwą fluidalną (grupa D wg Geldarta). Eksperymentalnie wyznaczono spadki ciśnienia przy przepływie gazu przez złoże i pustą kolumnę. Korzystając z równań literaturowych, obliczono opory przepływu na złożu, dystrybutorze gazu, prędkość krytyczną i prędkość wywiewania oraz porównano otrzymane wyniki z danymi doświadczalnymi. Metodą prób i błędów znaleziono równanie najlepiej przedstawiające pracę badanego układu fluidalnego, określono wpływ eksploatowanego sita na spadki ciśnienia występujące w trakcie procesu oraz zweryfikowano jego stosowalność w innych warunkach.

Słowa kluczowe: fluidyzacja, reaktor fluidyzacyjny, sito, hydrodynamika

Nomenclature

Ar – Archimedes number, –
c_D – drag coefficient, –
D – diameter of column, m
d_o – diameter of hole in the sieve bed, m
d_p – diameter of a particle, m
f – ratio of cross-sectional area of the orifice to cross-sectional area of the distributor, –
g – acceleration of gravity, $m \cdot s^{-2}$
H – height of fluidised bed, m
H_{mf} – height of fluidised bed at minimum fluidising conditions, m
H_0 – height of the stationary fluidised bed, m
Ly – Laszczenka number, –
n – number of rotameter plots, –
Δp – pressure drop across the bed, Pa
Δp_d – pressure drop across a distributor, Pa
Δp_{mf} – pressure drop across the bed at minimum fluidising conditions, Pa
Re – Reynolds number, –
Re_{mf} – Reynolds number at minimum fluidising conditions, –
Re_t – Reynolds number at falling conditions, –
S_{cz} – area of particle, m^2
u – gas velocity, $m \cdot s^{-1}$
u_{mf} – gas velocity at the minimum fluidising conditions, $m \cdot s^{-1}$
u_0 – gas velocity through an orifice, $m \cdot s^{-1}$
u_{op} – velocity of falling particle, $m \cdot s^{-1}$
u_t – terminal velocity, $m \cdot s^{-1}$
V_{cz} – volume of solid particle, m^3
ε – bed porosity, –
ε_{mf} – bed porosity at minimum fluidising conditions, –
ε_0 – porosity of stationary bed, –
μ_g – dynamic viscosity, $Pa \cdot s$
ξ – Localloss coefficient, –
ρ_g – gas density, $kg \cdot m^{-3}$
ρ_s – solid density, $kg \cdot m^{-3}$
σ – thickness of the sieve plate, m
φ – shape factor, –
ψ – sphericity of particle, –

1. Introduction

At the beginning of the twentieth century, Fritz Winkler discovered the phenomenon of fluidisation, observing that the movement of an air flow caused the bulk material to loosen and created a suspension in which the solid particles are in a chaotic motion. This initiated the very rapid development of fluid technology and its wide application in many industries. The main reason for this is a number of advantages of the fluidisation process, such as: significant intensification of the mass and heat exchange process through the use of very small sized particles of the dispersed phase, which results in extending the contact surface of the solid with the liquid without causing an increase in pressure loss; the possibility of carrying out the process on a continuous basis; thorough and rapid mixing, which makes the fluidised bed can be function as an isothermal system [1–3].

The most common unit operations performed in fluidised bed apparatus are solidification and granulation, coating, drying, adsorption and heat exchange processes. Fluid techniques also encounter difficulties such as: uneven residence time of particles in the reactor; the formation of disturbances causing heterogeneity of the fluidised bed; attrition of grains, walls of the apparatus and other elements placed in the bed; large complications related to the formation of clusters of particles and their sintering [1, 2]. In order to solve some of these problems, various construction solutions are applied, both for the construction of the grate itself and for the whole apparatus; furthermore, it is important to exert as much control over the process as possible from the design stage using many correlations to determine the relevant optimal parameters.

The fluidisation process is a complex problem in which many physicochemical factors are taken into account, such as hydrodynamics of flow around solid particles, hydrodynamics of fluid flow through channels, heat exchange, and mass. This has generated a lot of interest from scientists and has prompted a multitude of works addressing many important issues in this area allowing further improvement and progress in the field of fluid technology applications [1, 2, 4]. Winkler has made the first attempt of the industrial application of fluid technology to gasifying coal in a moving bed [5]. The next step was made around 20 years later when the process of fluid catalytic cracking (FCC) was widely used. The similarity of the fluidised bed to the liquid made it possible to control losses of the catalyst, which up to now had been very quickly deactivated during cracking due to the accumulation of carbon particles [5]. Fluid technology has subsequent been applied in the Fisher-Tropsch process, in which it increases synthesis efficiency and extends the life of the catalyst; addionally, it has applications in polymerisation and metallurgy for such processes as roasting and calcination [5, 6]. Other chemical reactions using a fluidised bed are partial oxidation, reforming of oil fraction and halogenation. Fluidisation is used in performing all thermal decomposition processes, such as: combustion (coal, biomass, waste), pyrolysis (coal, biomass), gasification of coal, biomass or plastic waste, and degassing.

Many advantages of fluidisation are widely exploited in the field of chemical and process engineering in a variety of physical processes [1, 5, 7, 8]. The most popular applications of fluidisation technology include:

- the purification and dedusting of waste gases in devices such as various types of scrubbers and fluidised filters – the absorption of pollutants in such apparatus is performed in three-phase systems (purified gas, liquid spraying, solid particles);
- heat exchange through fluid exchangers;
- drying – fluidised bed driers enable lower energy consumption than convection dryers and can be successfully used for drying various bulk materials (salt, cement, pharmaceutical products), pastes and sludges (sewage sludge), and secondary fuels (SRF);
- freezing – a cooled fluid stream receives heat from the frozen material, mainly food, such as fruits or vegetables;
- crystallisation – in the case of a fluidised bed crystalliser, it is possible to obtain a homogeneous product in terms of dimensions and crystals; during homogeneous fluidisation, almost perfect classification may occur – crystals of the largest size are organised at the bottom, while smaller crystals float at the top of the fluidised bed;
- sorting – classification of different particle sizes in the fluidisation process – the bed undergoes differentiation up the height of the apparatus with the heavier phases occupying the part of the column closer to the bottom and the lighter phases, consisting of smaller size particles or density, being lifted higher in up the column;
- disintegration and grinding of the material – turbulent movement of the solid causes its disintegration – this is used in fluidised jet mills;
- granulation – mainly used for the production of fertilisers in the form of granules (e.g. ammonium nitrate), for the production of catalysts used in the petrochemical industry, and for the production of various small food products (instant coffee, granulated tea) and pharmaceutical granules – this process can be performed in two ways by spraying the liquid on the surface of the particles or by the addition of a binder;
- coating (encapsulation) – performed in the same manner as granulation through the use of dry technology (binder addition) or wet technology (liquid drop dispersal) and used in the food and pharmaceutical industry;
- mixing.

The use of fluid technology enables increasing the efficiency of receiving the product while reducing production costs and emissions to the atmosphere. Meeting the restrictions imposed by the European Union is a fundamental challenge for the industry during the ecological era, which is why fluid technology is widely developed in combustion processes, where the emission level is the highest. Use of the liquefaction technique allows the simultaneous combustion and desulfurisation of fuels by bringing the appropriate sulphur-binding sorbents to the bed, and also reduces NO_x emissions to the atmosphere (this process has a low combustion temperature of around 800–900°C). In addition, the use of this type of furnace ensures a high rate of heat exchange in the furnace chamber and increases fuel combustion efficiency due to the thorough mixing and long residence time of particles in the bed, which results in the possibility of using smaller sized appliances and conducting the process at lower temperatures. The advantage of this application is also the possibility of using biomass, all kinds of enery-rich waste or low-grade coal with a high sulfur content as raw material. The popularity of this solution is already evident in global trends, where in

recent years, many powerplants have started using fluidised bed furnaces. In 2008, the largest supercritical boiler with a circulating fluidised bed with a capacity of up to 460 MW and powered with hard coal was commissioned at the Łagisza powerplant in Poland. Of course, this has not been in the leading position with regard to capacity for a long time, in recent years many other fluidised bed boilers have been put into use, in South Korea alone, one plant in 2015 produced four new devices, each with a capacity of 550 MW [1, 5, 7–9].

2. Theoretical section

The fluidised bed occurs in a range of fluid velocities between the minimum fluidisation velocity and terminal velocity. In this range, pressure drops are assumed to be permanent. It is important to initially determine the characteristic velocity of the selected system in order to determine the fluidisation conditions corresponding to the considered process.

The minimum fluidisation velocity is the value describing the state in which the fluid overpressure equates with the pressure exerted by the bed, i.e. the minimum speed needed to disturb the stability of the stationary bed and start the fluidisation process. This moment presents the equation:

$$\Delta p_{mf} = (1 - \varepsilon_{mf}) \cdot g \cdot (\rho_s - \rho_g) \cdot H_{mf} \tag{1}$$

When the bed parameters are known at the moment of minimum fluidisation, the Ergun formula can be used to calculate the minimum fluidisation velocity; this describes the dependence of the pressure drop in the bed on the fluidisation velocity:

$$\frac{\Delta p}{H} = 150 \cdot \frac{(1-\varepsilon)^2 \cdot \mu_g \cdot u}{\varepsilon^3 \cdot (\psi \cdot d_p)^2} + 1.75 \cdot \frac{(1-\varepsilon) \cdot \rho_g \cdot u^2}{\varepsilon^3 \cdot \psi \cdot d_p} \tag{2}$$

After entering the number of Re and Ar into this equation and transforming it due to the conditions of the beginning of the fluidisation, we get:

$$Ar = 150 \cdot \frac{(1-\varepsilon_{mf})}{\varepsilon_{mf}^3 \cdot \psi^2} \cdot Re_{mf} + 1.75 \cdot \frac{1}{\varepsilon_{mf}^3 \cdot \psi} \cdot Re_{mf}^2 \tag{3}$$

Equation (3) can be simplified for the appropriate flow range and after receiving the value of the Reynolds number, calculate the rate of fluidisation starting from it.

For laminar flow $(Re_{mf} > 20)$, the Ergun formula takes the form:

$$Ar = 150 \cdot \frac{(1-\varepsilon_{mf})}{\varepsilon_{mf}^3 \cdot \psi^2} \cdot Re_{mf} \tag{4}$$

And for turbulent flow $(Re_{mf} < 1000)$:

$$Ar = 1.75 \cdot \frac{1}{\varepsilon_{mf}^3 \cdot \psi} \cdot Re_{mf}^2 \qquad (5)$$

There are a number of equations in the literature allowing the calculation of the velocity at the beginning of fluidisation that have been proposed by many authors; however, they are limited by some ranges of applicability and not all are suitable for selected operating conditions.

In case the porosity or sphericity is unknown, it is to use the experimental equations, for example:

Grace's correlation:

$$Re_{mf} = (27.2^2 + 0.0408 Ar)^{0.5} - 27.2 \qquad (6)$$

Wen and Yu correlation:

$$Re_{mf} = (33.7^2 + 0.0408 Ar)^{0.5} - 33.7 \qquad (7)$$

Thonglimp's correlation:

$$Re_{mf} = (31.6^2 + 0.0425 Ar)^{0.5} - 31.6 \qquad (8)$$

Unfortunately, the experimental equations can lead to certain errors and do not describe every type of deposit well [10].

A different way to calculate the minimum fluidisation velocity is to use the critical Reynolds number $Re_{kr} = Re_{mf}$, which calculated from its relationship with Ar also allows calculation of the approximate velocity at the beginning of fluidisation:

$$Re_{mf} = Re_{kr} = 1.08 \cdot 10^{-3} \cdot Ar^{0.94} \qquad (9)$$

Pressure losses arise as a result of many reasons, such as: friction of the stream against the column wall, grains rubbing against each other and also friction between grains and the fluidising fluid, while the biggest influence here is the the issue of maintaining particles in a fluidised state. The pressure drop for the medium flowing through the material layer is defined by the formula [11]:

$$\Delta p = (1 - \varepsilon) \cdot g \cdot (\rho_s - \rho_g) \cdot H = (1 - \varepsilon_0) \cdot g \cdot (\rho_s - \rho_g) \cdot H_0 \qquad (10)$$

Many equations are known for which knowledge of the bed parameters at any point in the process is not necessary, for example:

Gibilaro's equation (for laminar and turbulent motion) [12]:

$$\frac{\Delta p}{H} = \left(\frac{17.3}{Re} + 0.336 \right) \cdot \frac{\rho_g \cdot u^2}{d_p} (1-\varepsilon) \cdot \varepsilon^{-4.8} \qquad (11)$$

Kozeny's equation (low values of Reynolds number) [13]:

$$\frac{\Delta p}{H} = 180 \cdot \frac{(1-\varepsilon)^2 \cdot \mu_g \cdot u}{g \cdot \varepsilon^3 \cdot d_p^{\,2}} = \frac{5 \cdot (1-\varepsilon)^2 \cdot \mu_g \cdot u}{g \cdot \varepsilon^3 \cdot \left(\dfrac{V_{cz}}{s_{cz}} \right)^2} \qquad (12)$$

Burke-Plummer's equation ($Re > 1000$) [4]:

$$\frac{\Delta p}{H} = 1.75 \cdot \frac{(1-\varepsilon) \cdot u \cdot \rho_g}{d_p \cdot \varepsilon^3} \qquad (13)$$

Lev's equation ($Re < 20$) [12]:

$$\frac{\Delta p}{H} = \frac{200 \cdot \mu_g \cdot u \cdot (1-\varepsilon_{mf})^2 \cdot \varphi^2}{d_p^2 \cdot \varepsilon_{mf}^{\,3}} \qquad (14)$$

Kozeny-Carman's equation:

$$\frac{\Delta p}{H} = 180 \cdot \frac{u \cdot \mu_g \cdot (1-\varepsilon)^2}{(d \cdot \Psi)^2 \cdot \varepsilon^3} \qquad (15)$$

The terminal velocity is the velocity equal to the free falling velocity of the particles, the exceeding of which is equivalent to the end of the fluidisation process and exhaustion of the granular material from the reactor. It is therefore the maximum speed at which the fluidisation process can take place and is calculated from dependence:

$$u_{op} = \sqrt{\frac{4 \cdot d_p \cdot (\rho_s - \rho_g) \cdot g}{3 \cdot c_D \cdot \rho_g}} \qquad (16)$$

Another way to determine terminal velocity for a certain bed is to use the Archimedes and Laszczenko numbers [10]:

$$Ar = \frac{d^3 \cdot (\rho_s - \rho_g) \cdot g \cdot \rho}{\mu^2} \qquad (17)$$

$$Ly = \frac{Ar^2}{(18 + 0.61\sqrt{Ar})^3} \tag{18}$$

$$u_{op} = \sqrt[3]{\frac{Ly \cdot (\rho_s - \rho_g) \cdot g \cdot \mu_g}{\rho^2}} \tag{19}$$

3. Experimental section

3.1. The bed material and the fluidising agent

The research applied a porous fluidised bed – a type of quartz sand (SiO_2), a chemically inert material. The stationary bed had a height of 0.7 m. The material according to the division of Geldart was classified in group D. The fluidising medium of the bed was air at an average temperature of 40°C, which was experimentally determined during the tests. The basic parameters characterising the bed and air are presented in Table 1.

Table 1. Parameters of fluidising gas and bed material

Parameter	Unit	Value
fluidising gas – air		
μ_g	Pa · s	$1.927 \cdot 10^{-5}$
ρ_g	kg · m^{-3}	1.129
Granular material – porous fluidised bed		
ε	–	0.364
d_p	m	$0.875 \cdot 10^{-3}$
ρ_s	kg · m^{-3}	2629
φ	–	1.08

3.2. Research methodology

In the first part of the research, a series of measurements was made for a column filled with granular material. The bed material was brought to a fluidised state by gradually increasing the linear velocity of the gas from 0 m · s^{-1} to 4 m · s^{-1} whilst simultaneously reading the pressure drops on the pressure gauge. In the next step, the above procedure was repeated in the opposite direction, i.e. the gas velocity was reduced from maximum to zero. In the second part of the research, the bed was removed and the pressure drops were measured in an empty reactor as a function of gas velocity.

3.3. Test stand

The tests were preformed in a column with a circular cross section with a diameter D of 0.074 m. The quantity of the particles in the the fluidised bed was controlled by filtering through sieves placed at the bottom and top of the column. The bottom sieve also served as a gas distributor. The parameters of the sieve are summarised in Table 2.

Table 2. Catalogue data regarding the sieve according to the manufacturer Ann-Filters [15]

Parameter	Unit	Value
mesh size	mm	0.65
diameter of the wire	mm	0.3
width of the grid	mm	1000
open area	%	47
number of mesh pores per 1 cm	$m \cdot cm^{-1}$	11
number of mesh pores per 1 cm²	$m \cdot cm^{-2}$	111
weight 1m²	kg	1.20
type of weave	–	woven
type of material	–	stainless steel
steel grade acc. AISI	–	AISI 304

The general scheme of the fluidised bed reactor is shown in Fig. 1.
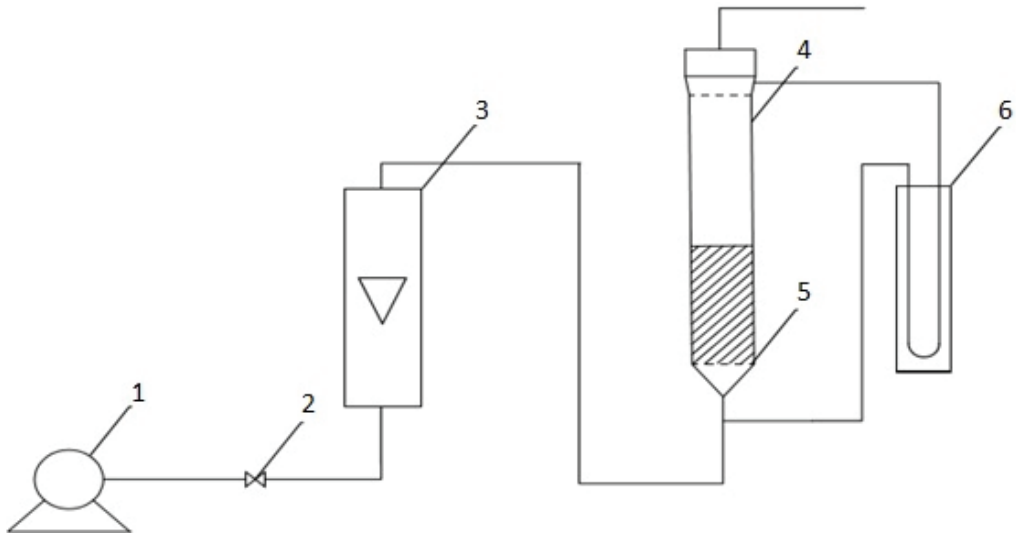

Fig. 1. Schematic diagram of the test installation: 1 – blower, 2 – regulating valve, 3 – rotameter, 4 – fluidisation column, 5 – gas distributor, 6 – water manometer [source: own material]

4. Results and discussion

4.1. Resistance of gas flow through a fluidised bed and an empty reactor

The obtained curve (Fig. 2) is uncharacteristic of a fluidisation process. There was no stabilisation of pressure drops that are typical of fluidisation. While lowering the gas velocity, a higher flow resistance was recorded than when its velocity was increased. This is due to the polydispersity of the fluidised bed. For particles with a smaller diameter, the gas velocity exceeded the value of their free fall velocity sooner than in the case of the other particles. Therefore, they were exhausted from the bed and stopped by a sieve mounted at top of the column, thus creating additional resistance.
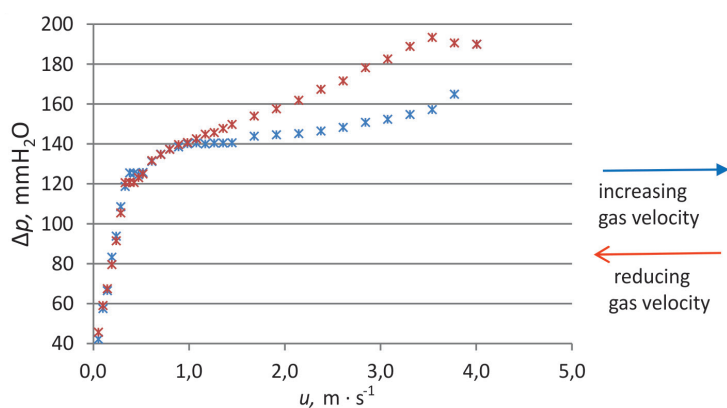

Fig. 2. Graphic representation of the dependence of the gas pressure drop in the fluidisation process on its velocity

After the second part of the research, an exponential increase in the resistance of gas flow through the empty reactor was observed along with the increase of gas velocity (Fig. 3).
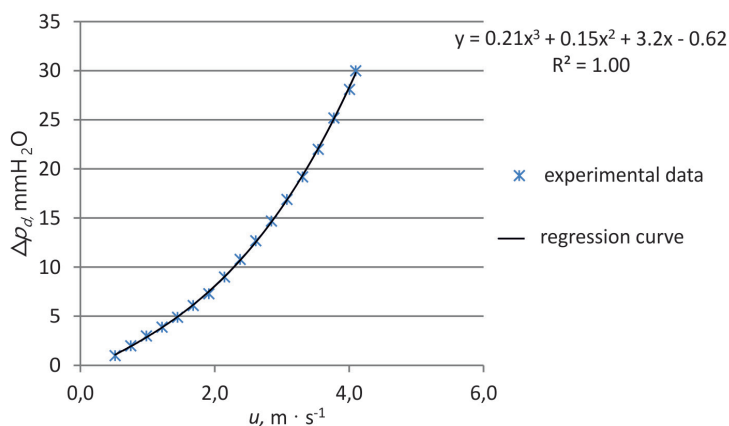

Fig. 3. Graphic representation of the dependence of the pressure drop in the empty column on the gas velocity

When the pressure drops generated by the sieve plate and the sieve closing the reactor from the top were taken into account, a characteristic curve of only the working fluidised bed was obtained (Fig. 4); this was characterised by constant resistance to gas flow as its velocity increased. Initial fluctuations in the pressure drops may be due to an uneven material grain diameter; these grains were suspended at different velocities of the fluidising medium.
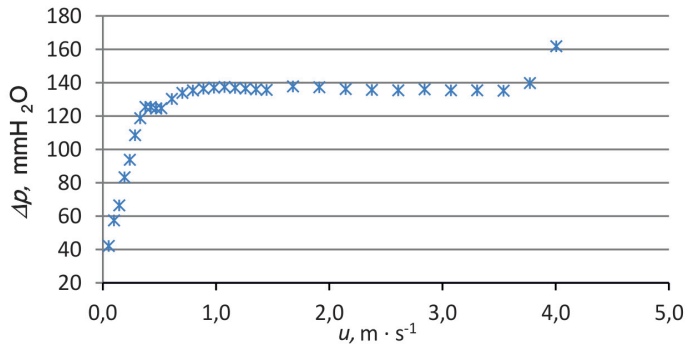

Fig. 4. Graphic representation of the dependence of the pressure drop in the fluidised bed on gas velocity

4.2. Theoretical calculations of process parameters

4.2.1. Gas flow resistance in a fluidised bed

Analysing the obtained experimental data, the approximate value of the minimum fluidisation velocity was determined as $u_{mf} = 0.4$ m · s^{-1}. The average value of pressure losses generated by the fluidised bed was $\Delta p_{śr} = 134$ mm H$_2$O. In order to assess the suitability of the equations of different authors in the literature to describe the hydrodynamics of the fluidised bed, the pressure drops for the experimental value u_{mf} were calculated (Table 3).

Table 3. List of calculation results for pressure drops on the bed

Δp calculated, mmH$_2$O		$\Delta p_{śr}$, mmH$_2$O	Absolute error, mmH$_2$O	Relative error, %
Author	Value			
Ergun (2)	120		14	11.7
Gibilaro (11)	139		5	3.6
Kozeny (12)	155	134	21	13.5
Kozeny-Carman (15)	124		10	8.1
Lev (14)	138		4	2.9

By comparing the value of the average pressure drop during the actual fluidisation determined on the basis of experimental data with the losses obtained by theoretical calculations, it can be observed that the results are similar; however, not all give a satisfactory result. A certain error probably generates an inaccurate determination of the minimum

fluidisation velocity on which the calculated pressure drop depends. In addition, the equations used are mainly empirical equations, so the values obtained with them may differ from the values obtained during this experiment. The correlations that best capture the dependence of the pressure drop on the gas velocity for the given operating conditions appear to be the Lev (14) and Gibilaro (11) equations.

4.2.2. The minimum fluidisation velocity

Using the known dependences of the velocity of the fluidising medium and the pressure drop on the bed, the critical velocity values for the average pressure drop determined on the basis of the experiment were calculated ($\Delta p_{śr}$ = 134 mm H$_2$O). The results are summarised in Table 4.

Table 4. Set of theoretical calculations of critical speed for the tested bed

m · s^{-1}		u_{mf}, m · s^{-1}	Absolute error, m · s^{-1}	Relative error, %
Author	Value			
Ergun (2)	0.48		0.08	16.7
Gibilaro (11)	0.39	0.4	0.01	2.6
Kozeny (12)	0.49		0.09	18.4
Kozeny-Carman (15)	0.49		0.09	4.8

To obtain search velocity, the equation defining the Reynolds number and correlations binding the Reynolds number with the Archimedes number using appropriate constants were used [12]:

$$Re_{mf} = \sqrt{C_1^2 + C_2 \cdot Ar} - C_1 \tag{20}$$

Table 5. Summary of theoretical calculations of the critical velocity for the tested fluidised bed
(constans C_1, C_2: [12])

Author	Ar	C_1	C_2	Re_{mf}	u_{mf}, m · s^{-1}	Absolute error, m · s^{-1}	Relative error, %
Wen and Yu		33.7	0.0408	24	0.46	0.06	13.0
Richardson		25.7	0.0365	25	0.49	0.09	18.4
Saxen Vogel		25.3	0.0571	35	0.68	0.28	41.2
Babu and others	52 000	25.25	0.0651	38	0.75	0.35	46.7
Grace		27.2	0.0408	26	0.52	0.12	23.1
Chitester		28.7	0.0494	30	0.58	0.18	31.0

Comparing the critical speed values obtained by theoretical calculations, one can observe quite a large spread of results. The effect that most deviates from the real effect ($\delta u_{mf} = 47\%$) is that resulting from the equation proposed by Babu. The dependencies of Chitester, Grace, Saxen and Vogel also do not work, which is probably due to a matter of the constants that were experimentally fitted by these researchers not being proper for the tested bed.

4.2.3. Terminal velocity

a) Calculation of the terminal velocity:
- from the equation to the free falling of solid particles (20):

$$u_t = 7.4 \text{ m} \cdot \text{s}^{-1}$$

- from the *relationship* between the Archimedes and Laszczenko numbers described by equations (17), (18):

$$u_t = 5.5 \text{ m} \cdot \text{s}^{-1}$$

- from the formula proposed by Gumz and Frössling for Reynolds numbers in the range of $3 \cdot 10^2 \leq Re_t \leq 2.5 \cdot 10^3$ [16]:

$$\frac{1}{Re_t} = \frac{21.35}{\log \dfrac{\Psi}{0.065}} \cdot \frac{1}{Ar} + \sqrt{\frac{2.593 - 2.382 \cdot \Psi}{Ar}} \tag{21}$$

$$u_t = 6.3 \text{ m} \cdot \text{s}^{-1}$$

Results obtained by means of the above equations give quite diverse values of suspension speed; perhaps this is due to the origin of the equations. The first two are equations of theoretical origin; they refer to the calculation of the falling speed of a single particle, but they do not take into account the influence of the interaction of other grains or the sphericity of the particles. The equation of Gumz and Frössling is one of many empirical equations proposed to calculate the suspension velocity which does the impact of these factors take into account.

Fig. 4 shows the experimental data printed, it can be read that the suspension speed was approx. $u_t = 4.0 \text{ m} \cdot \text{s}^{-1}$. During the tests, however, this speed was not observed. At the gas velocity value of 4.0 m $\cdot$ s^{-1} the bed remained in a state of fluidisation. A sudden drop in pressure could be caused by the lifting up of individual grains coming from the smallest fraction of material, which caused clogging of the upper sieve.

4.2.4. Gas flow resistance at the distributor

The equation showing the increasing dependence of pressure drops generated by the grate as a function of the speed of the fluidising medium $\Delta p_d = f(u)$ was adjusted (Fig. 3). This dependence can be determined with high accuracy using the following correlation [11]:

$$\Delta p_d = 0.21 \cdot u^3 + 0.15 \cdot u^2 + 3.2 \cdot u - 0.62 \tag{22}$$

a) Calculation of pressure drops on the sieve

Pressure drops on the sieve were calculated using:

▸ Pavlov's equation:

$$\Delta p_d = \frac{0.503 \cdot u_0^2 \cdot \rho_g \cdot (1 - f^2)}{C^2} \tag{23}$$

▸ Malakonov's equation:

$$\Delta p_d = \xi \cdot \frac{u^2 \cdot \rho_g}{2 \cdot f^2} \tag{24}$$

$$\xi = 1.75 \cdot (1 - f)^2 \cdot \left(\frac{d_o}{\delta}\right)^2 \tag{25}$$
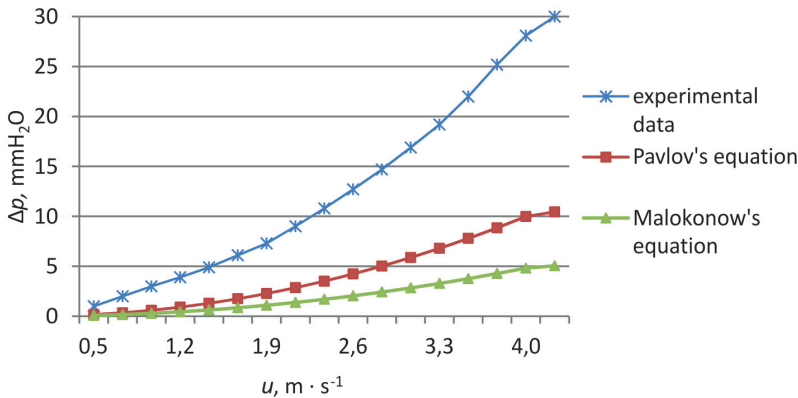
$$\xi = 0.577$$

Fig. 5. A graph that summarises the results of theoretical calculations of pressure drops on a gas distributor with experimental data

Considering the results of pressure drops produced by the sieve plate, it can be concluded that the plate does not cause sufficient resistance to the gas flow. This resistance is simultaneously large enough to significantly affect the hydrodynamics of the process. According to the literature, a well-designed gas distributor should fulfill the dependence $\Delta p_d = (0.2{-}0.4) \cdot \Delta p$, to ensure process stability. The sieve used in the tests, due largely to the high clearance value (0.47), results in much lower pressure drops. This causes non-compliance of the experimental results with the values calculated using the formulas proposed by Pavlov and Molokonov. The Pavlov equation gives the value of the open area in the distributor plate as the value often accepted as $0.01{-}0.04$, which illustrates the deviation of the tested sieve

from his equation (Fig. 5). As a result, unfortunately, none of the correlations used to calculate local pressure losses on the sieve led to results similar to the empirical results; therefore, it does not describe the work of the selected gas distributor well.

5. Summary and conclusions

For the tested air-solid system, the best equation for determining the pressure drops occurring in the fluidisation state was the equation proposed by Gibilaro (11). When taking into account critical velocity, it is also the dependence given by Gibilaro that yields the best result. This gives valuable information that it is the equation that best describes the dependence between pressure drops and gas velocity for the tested bed. This is the case for fluidised bed and takes into account the losses caused by the pore size and the occurrence of contraction [4].

An important issue in the application of fluid technology, which is well illustrated by the results of the experiment, is the control of the grain size of the layer material. A bed with a given, representative value of the particle diameter contains finer fractions. Even a small difference in grain size affects the hydrodynamic parameters of the system, causes clogging of the upper sieve and uncontrolled pressure drops and material loss.

The sieve used in the tests has a significant influence on the gas flow resistance through the fluidisation reactor, despite the high clearance value (0.47). The effect of this resistance should be taken into account at the design stage of the fluidisation apparatus. Of the equations that are presented in the paper showing gas pressure drops as a function of its velocity on the distributor, neither those of Molokonow nor those of Pavlov describe the operation of the tested sieve to a satisfactory level of accuracy.

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Adrian Chajec orcid.org/0000-0001-5329-9534
adrian.chajec@pwr.edu.pl

Kamil Krzywiński orcid.org/ 0000-0002-5562-9602

Łukasz Sadowski orcid.org/0000-0001-9382-7709
Faculty of Civil Engineering, Wroclaw University of Science and Technology

Krzysztof Ostrowski orcid.org/0000-0001-5047-5862
krzysztof.ostrowski.1@pk.edu.pl
Institute of Building Materials and Structures, Cracow University of Technology

The influence of polypropylene fibres on the properties of fresh and hardened concrete

Wpływ dodatku włókien polipropylenowych na właściwości mieszanki betonowej oraz betonu stwardniałego

Abstract

The purpose of the article is to determine the effect of the addition of polypropylene fibres on the properties of concrete mixtures and hardened concrete. To this end, both destructive and non-destructive tests were conducted. The concrete mixture tests included the testing of the consistency, air content and bulk density of the concrete mixture. Investigations of hardened concrete were based on the determination of compressive strength by destructive tests, sclerometer and ultrasonic methods and tensile strength in bending tests. All tests were performed for seven series of concrete mixtures, differing in their fibre content. The results showed that the addition of polypropylene fibres to the concrete mixture causes changes in consistency, increases air content, and does not increase the compressive and tensile strength of concrete. It was also observed that the addition of polypropylene fibres does not cause significant changes in the bulk density of the concrete mix.

Keywords: fibre-reinforced concrete, polypropylene fibres, dispersed reinforcement, fresh concrete mixture, hardened concrete

Streszczenie

Tematem artykułu jest określenie wpływu dodatku włókien polipropylenowych na właściwości mieszanki betonowej oraz betonu stwardniałego. W tym celu przeprowadzono badania świeżej mieszanki betonowej oraz betonu stwardniałego (niszczące oraz nieniszczące). W skład badań mieszanki betonowej wchodziły: badanie konsystencji mieszanki betonowej, badanie zawartości powietrza w mieszance betonowej, badanie gęstości objętościowej mieszanki betonowej. Badania betonu stwardniałego opierały się na pomiarze wytrzymałości betonu na ściskanie, wytrzymałości betonu na rozciąganie przy zginaniu, wytrzymałości betonu na ściskanie metodą sklerometryczną oraz wytrzymałości betonu na ściskanie metodą ultradźwiękową. Wszystkie badania zostały wykonane dla siedmiu serii mieszanek betonowych, różniących się od siebie zawartością włókien. Dodatek włókien polipropylenowych do mieszanki betonowej powoduje zmiany jej konsystencji oraz podwyższenie w niej zawartości powietrza. Włókna polipropylenowe nie powodują istotnych zmian gęstości objętościowej mieszanki betonowej.

Słowa kluczowe: fibrobeton, włókna polipropylenowe, zbrojenie rozproszone, mieszanka betonowa, beton stwardniały

1. Introduction

Reinforcement in the form of fibre additives has been used in concrete mixtures for a long time [1, 5, 6]. The basic purpose of adding fibres to the cement matrix is to provide homogeneous properties, regardless of the direction of load [3, 4]. Steel fibres are the most commonly used [22, 24, 25], although polypropylene fibres are increasingly added to the concrete mixture. The characteristics of the changes implemented in the properties of concrete mix and hardened concrete caused by the addition of fibres is a complicated phenomenon and depends upon many factors [1, 3, 4, 8, 10, 23, 25].

The properties of the concrete mix influence its suitability for forming parts of structural elements in building structures [1, 5, 7, 9, 14, 22]. In this context, several technological regimes introduce a number of requirements for the properties of a concrete mixture, including those with the addition of fibres, such as: adequate consistency, limited air content, a specific volume density [5, 14–17]. In order to understand the impact of fibre addition on the properties of a concrete mixture, those properties should be examined [8, 13, 17].

The use of fibres for the sole purpose of improving the mechanical properties of concrete is the most common reason for their addition [4, 8, 14, 16]. Steel fibres can affect the mechanical properties of hardened concrete; this has been proven many times [4, 5]. The present research was conducted to determine the impact of polypropylene fibres on the properties of both concrete mix and hardened concrete.

2. Materials

2.1. Methodology

In order to determine the impact of polypropylene fibres on the properties of both concrete mixture and hardened concrete, a study was designed consisting of two main stages: fresh concrete mix tests and hardened concrete tests (after 28 days of curing). The concrete mixture tests included: consistency tests using the slump test (in accordance with PN-EN 12350-2); air content tests (according to PN-EN 12350-7); bulk density tests (according to PN-EN 12350-6). The tests carried out on hardened-concrete samples were: compressive strength tests of concrete (in accordance with PN-EN 12390-3); concrete tensile strength tests in bending (in accordance with PN-EN 12390-5); concrete compressive strength tests using a sclerometric method (according to [2]); examination of the compressive strength of concrete using ultrasound (according to [13]). The tests were performed for seven series of concrete samples (Table 1) with different proportions of fibres.

Table 1. Fibre content for each concrete series

Number of series	Fibre content [%]
FP0	0.0
FP1.5	1.5
FP2.0	2.0
FP2.5	2.5
FP3.0	3.0
FP3.5	3.5
FP4.0	4.0

3. Components of concrete mixture

All mixes were prepared using cement type III 42.5 (320 kg/m³, Hranice, Czech Republic), sand φ0–2 mm (700 kg/m³, Byczeń, Poland), gravel φ2–8 mm (443 kg/m³, (Byczeń, Poland), gravel φ8–16 mm (700 kg/m³, Byczeń, Poland). Superplasticiser Pantarhit FM (3.84 kg/m³) were used to obtain workability of the concrete mixture. The amount of the polypropylene fibres was since 0 to 4.0 kg/m³. The concrete mixtures were made with the same proportions of ingredients and a constant water/cement ratio w/c = 0.5.
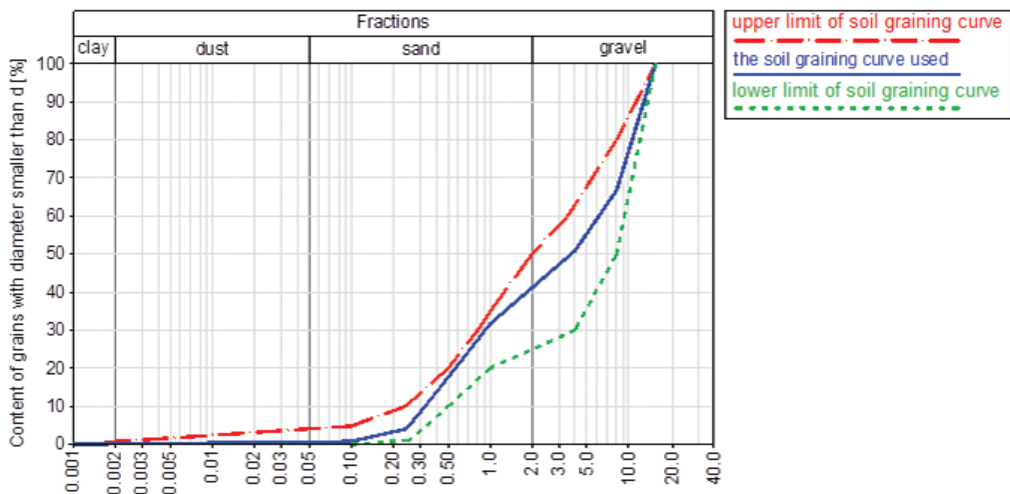
Fig. 1. Grain curve of mixture of aggregates used to make the concrete mixture in relation to the limit aggregate curves described in the standard [3]

A C25/30 class of concrete was designed. Fig. 1 shows the grain curve of the mixture of aggregates used in the concrete mixture. Polypropylene fibres with a length of 48 mm and a diameter of 0.6 mm were used for the tests. The manufacturer states that the average tensile strength of these fibres is 600 MPa, while the Young's Modulus is 5 GPa.

3.1. Preparation of specimens

The dry ingredients (with the specified amount of fibres) were mixed with 1/3 of the water for 30 seconds. The rest of the water was then added to the superplasticiser and the ingredients were mixed for 60 seconds. After mixing, the concrete mixture was tested. The mix used for the tests was then added to the remaining part in the mixer and mixed for 30 seconds. Following this, the concrete mixture was poured into previously prepared forms. After 24 hours, the samples were removed from the moulds and placed in containers with water for 28 days.

Fig. 2. Preparation of the concrete mixture: a) mixing of dry ingredients; b) weighing of the fibers; c) pouring concrete into the forms
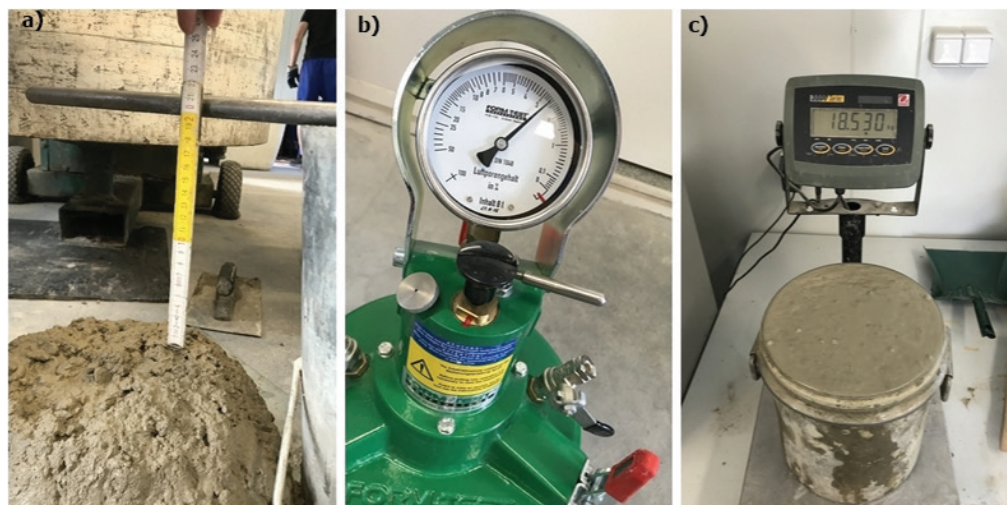
Fig. 3. Testing of the concrete mixture: a) slump test of the concrete mixture; b) air content test of the concrete mixture; c) bulk density test of the mixture

Fig. 4. Testing of the hardened concrete: a) sclerometric method; b) destructive test – uniaxial compression test; c) testing of concrete tensile strength under bending

4. Results and discussion

4.1. Fresh concrete mixture properties

Fig. 5 presents the results of the testing of the consistency of the concrete mix using the slump test (Fig. 3a) for the different proportions of fibre. Fig. 5 shows that the addition of polypropylene fibres to the concrete mixture results in a significant (about 10 cm) change in the slump value of the concrete mixture. This is due to the large surface area of the fibres added to the concrete mix, which requires a cement paste environment. This causes a reduction in the amount of remaining cement mortar in the concrete mixture and consequently, a change

in the consistency to a more dense plastic. It should also be noted that the addition of polypropylene fibres results in changes in the consistency of the concrete mixture from S4 to S3. In addition, a polypropylene fibre content above 3.0 kg/m³ reduces the consistency class to S2.
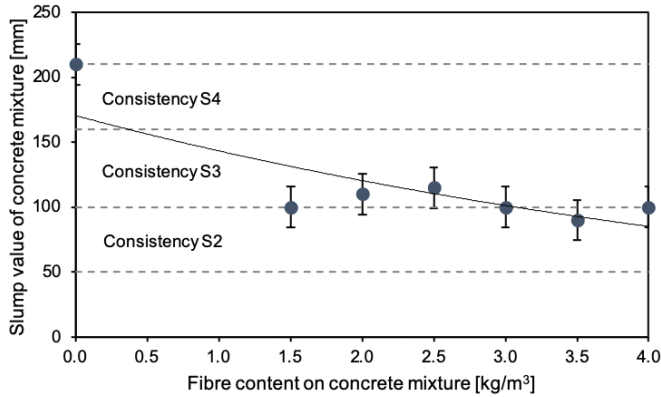

Fig. 5. Slump value of concrete mixture for the different proportions of polypropylene fibres

Fig. 6 presents the results of the air content test in a concrete mix dependent upon the polypropylene fibre content (Fig. 3b).

It can be seen from Fig. 6 that as the content of polypropylene fibres in the concrete mix increases, the air content also increases. The presence of fibre influences the heterogeneity in the concrete mixture and increases the number of voids.
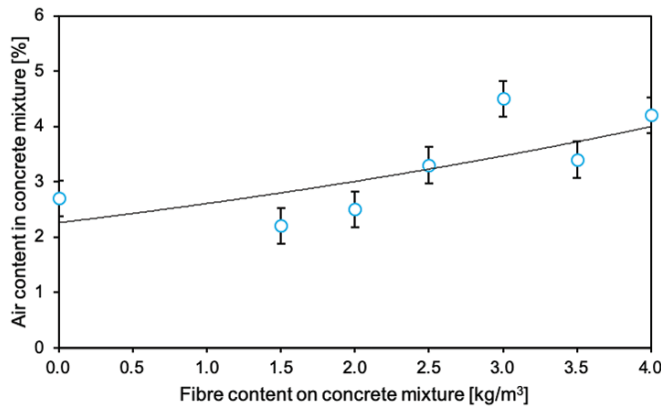

Fig. 6. Dependence of air content in concrete mix on the content of polypropylene fibres

Fig. 7 presents the results of the volume density test of the concrete mix dependent upon the content of polypropylene fibres (Fig. 3c).

It can be seen from Fig. 7 that the addition of polypropylene fibres has no significant effect on the bulk density of the concrete mix.
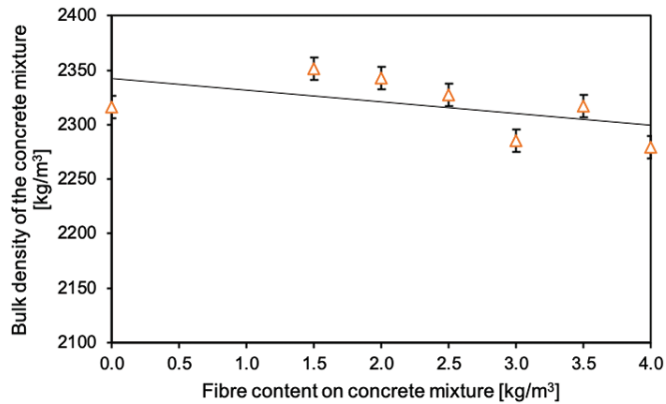
Fig. 7. Dependence of the bulk density of concrete mix on the content of polypropylene fibres

4.2. Testing of hardened concrete

Table 2 presents the results of tests of the compressive strength of concrete using ultrasound.

Table 2. The results of the compressive strength test of concrete using the ultrasound method

Concrete mix number	Sample number	Average velocity [m/s]	Compressive strength [Mpa]	Standard deviation [-]	Average Compressive strength [Mpa]
FP0	S1	4752.11	52		52.00
	S2	4632.57	50		
	S3	4802.84	54		
FP1.5	S1	4306.23	38		37.33
	S2	4298.58	38		
	S3	4257.39	36		
FP2.0	S1	4429.14	44		44.00
	S2	4407.68	44		
	S3	4424.88	44		
FP2.5	S1	4336.46	38	5.39	37.33
	S2	4299.79	36		
	S3	4335.43	38		
FP3.0	S1	4407.55	42		40.67
	S2	4468.94	44		
	S3	4258.09	36		
FP3.5	S1	4491.26	50		44.67
	S2	4362.28	42		
	S3	4348.72	42		
FP4.0	S1	4483.38	48		47.33
	S2	4403.49	46		
	S3	4439.94	48		

Fig. 8 shows the correlation curve used to determine the compressive strength of concrete using the sclerometric method.
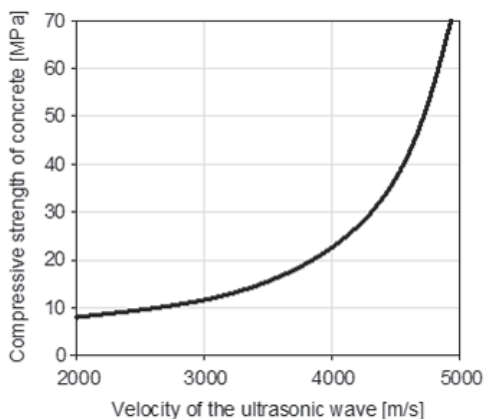

Fig. 8. Dependence of the compressive concrete strength on ultrasonic wave speed, based on [13]

Table 3 presents the results of concrete compressive strength tests using a sclerometric method.

Table 3. The results of the concrete compressive strength test using a sclerometric method

Specimen	L1	L2	L3	L4	L5	$\bar{L}$	R according to ITB210 [MPa]	$\overline{Rc}$ [Mpa]
FP0-1	31	34	30	28	34	31	18.44	
FP0-2	34	39	34	35	33	35	25.60	23.21
FP0-3	36	34	36	36	34	35	25.60	
FP1.5-1	32	32	30	33	34	32	20.10	
FP1.5-2	35	33	31	30	33	32	20.10	20.10
FP1.5-3	35	33	32	32	28	32	20.10	
FP2.0-1	34	33	32	34	32	33	21.85	
FP2.0-2	34	34	38	38	39	37	29.67	27.07
FP2.0-3	36	40	34	38	39	37	29.67	
FP2.5-1	36	36	34	38	32	35	25.60	
FP2.5-2	33	31	30	29	31	31	18.44	20.82
FP2.5-3	30	32	30	32	31	31	18.44	
FP3.0-1	38	34	32	33	34	34	23.69	
FP3.0-2	31	31	31	29	31	31	18.44	19.66
FP3.0-3	32	30	30	29	30	30	16.85	
FP3.5-1	32	32	35	31	30	32	20.10	
FP3.5-2	35	33	35	38	32	35	25.60	23.77
FP3.5-3	34	32	34	38	35	35	25.60	
FP4.0-1	34	30	31	34	30	32	20.10	
FP4.0-2	34	33	31	33	34	33	21.85	20.69
FP4,.0-3	36	32	30	31	33	32	20.10	

Fig. 9 shows the correlation curve used to determine the compressive strength of concrete using the sclerometric method.
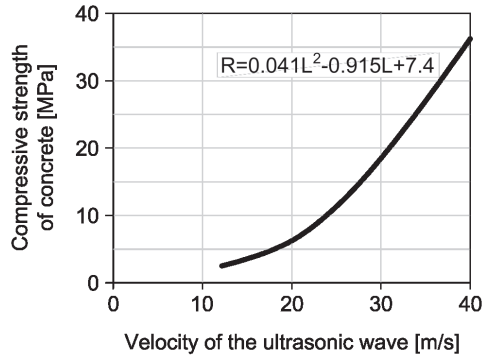

Fig. 9. L-R dependence curve according to ITB210 instructions, own elaboration based on [2]

Fig. 10 presents the results of concrete compressive strength tests using various methods: ultrasonic, sclerometric and destructive, dependent upon the content of polypropylene fibres.
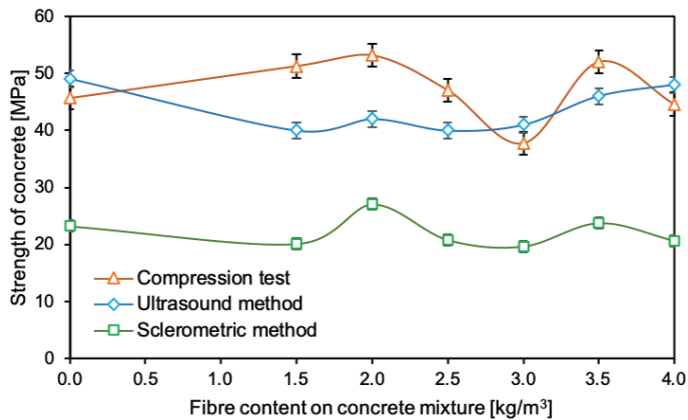

Fig. 10. The compressive strength of concrete, determined by different methods, dependent upon the content of polypropylene fibres

It can be seen from Fig. 10 that different values of the compressive strength were obtained depending upon the method according to which it was determined. The most accurate method is the destructive method. Attention should be paid to the similar course of strength diagrams pertaining to the sclerometric method and the destructive method; however, the values of determined strengths vary considerably. This is due to the fact that the sclerometric method determines the surface resistance of concrete compressive strength and is treated as an illustrative test. In turn, destructive testing is a more accurate method to assess the strength of concrete. Values obtained for concrete strength by the ultrasonic and destructive methods are similar to each other. No clear dependence of the compressive strength of concrete on the polypropylene fibre content was observed.

Fig. 11 presents the results of the tests of concrete tensile strength under bending dependent upon the content of polypropylene fibres (Fig. 4c).
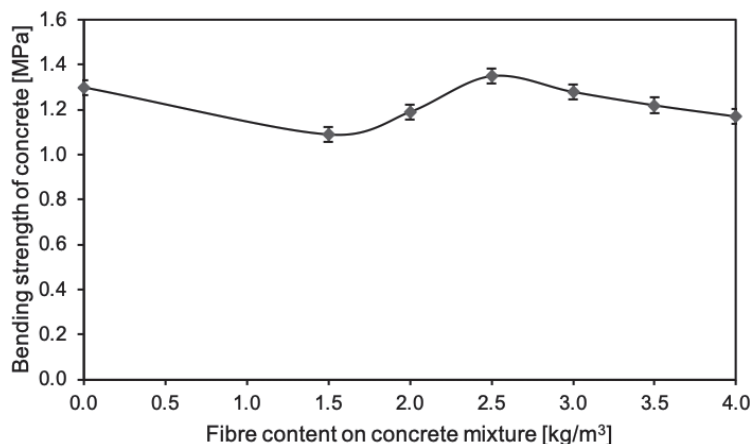

Fig. 11. Tensile strength of concrete in the bending test dependent upon the content of polypropylene fibres

It can be seen from Fig. 11 that the addition of polypropylene fibres does not significantly affect the concrete tensile strength under bending. The graph also does not show a clear relationship between the concrete tensile strength under bending and the content of polypropylene fibres.

5. Conclusions

The following conclusions may be drawn from the work presented in this paper:
- The consistency of a concrete mix depends on the proportion of polypropylene fibres.
- The air content in a concrete mix depends on the density of polypropylene fibres. Along with the increase of fibre content in the concrete mix, the air content also increases.
- The addition of polypropylene fibres to the concrete mix does not have a significant impact on its bulk density.
- The addition of polypropylene fibres to concrete does not increase its compressive strength.
- The tested value of the compressive strength of concrete depends on the method which was employed to determine it.
- The addition of polypropylene fibres does not increase the tensile strength of concrete during bending.

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Waldemar Małopolski orcid.org/0000-0001-6927-3320

malopolski@mech.pk.edu.pl
Production Engineering Institute, Faculty of Mechanical Engineering,
Cracow University of Technology

A method for the automatic creation of bidirectional transportation paths for AGVs in Delmia QUEST

Metoda automatycznego generowania dwukierunkowych dróg transportowych dla robotów mobilnych w programie Delmia QUEST

Abstract

In this paper, a method for the automatic creation of bidirectional paths for AGVs in the Delmia QUEST software application is presented. The layout of transportation subsystem can be prepared in a spreadsheet. Based on it the file with input data is generated. Using programming languages included in QUEST, procedures were created and based on these procedures, a macro was built. This macro allows reading input data from the file and creates the transportation paths automatically. This enables the simulation model building to be less time consuming.

Keywords: modelling, simulation, bidirectional paths, AGV, Delmia QUEST

Streszczenie

W artykule przedstawiono metodę automatycznego generowania dwukierunkowych dróg transportowych w programie Delmia QUEST dla autonomicznie sterowanych robotów mobilnych. Układ i rozmieszczenie dróg transportowych są projektowane w arkuszu kalkulacyjnym, a następnie zapisane jako dane wejściowe w postaci pliku tekstowego. Wykorzystując języki programowania zawarte w programie QUEST, opracowano odpowiednie procedury. Zostały one następnie wykorzystane do budowy macro, które wczytuje dane z pliku i w automatyczny sposób generuje całą sieć dróg transportowych. Dzięki temu budowanie modelu symulacyjnego może być uproszczone i przyspieszone.

Słowa kluczowe: modelowanie, symulacja, dwukierunkowe drogi, roboty mobilne, Delmia QUEST

1. Introduction

Transportation subsystems currently play a very important role in production systems. They are used to increase the flexibility and decrease the production costs. Nowadays, transportation subsystems are very often based on automated guided vehicles (AGVs). This kind of solution guarantees a high flexibility and efficiency. However, there are many problems associated with the AGVs construction and control; for example, some aspects of design and operational parameters of AGVs are presented in [1]. The biggest problem is to develop collision-free and deadlock-free methods of controlling AGVs. In this area, various research studies are still being conducted. For example, one method of handling deadlocks in automated manufacturing systems based on AGVs is described in [2] and an AGV scheduling algorithm and collision avoidance is presented in [3]. A cyclic scheduling problem with AGVs is presented in [4]. The concept of a distributed AGV control system is presented in [5]. A collision and deadlock free method for decentralised route planning in a dynamic environment is described in [6]. The assignment of suboptimal AGV routing and scheduling is considered in [7]. A novel paradigm for conflict resolution in multi-vehicle traffic systems is presented in [8]. A new approach to dynamic control of the motion of multiple mobile robots can be found in [9]. A genetics-based machine learning approach for collision free AGV control is presented in [10].

Simulation programs, especially commercial programs, are very often used in the design of production or transportation systems, including those with AGVs. In this area, 3D modelling and simulation capabilities are becoming increasingly available. One of the most popular software programs with full 3D functionality is Delmia QUEST. These types of simulation tools are used, for example, for the analysis of vehicle control and functionality together [11]. An approach for job shop scheduling based on a simulation approach is presented in [12]. The application of virtual reality in order to present a methodology for the requirement analysis of holonic manufacturing system design is shown in [13]. It is also possible to simulate the operation of a production line and estimate the number of pallets in workshops [14]. We can find many different applications of simulation to analyse the operation of production systems and transportation subsystems.

Using such powerful tools for the manual modelling of large and complex systems is very time consuming. Therefore, we can find different solutions to facilitate and speed up modelling, for example, a method of creating a simulation model in which production information is transferred through the extensible mark-up language (XML) is presented in [15], but this solution is dedicated to aircraft assembly production line. Other XML-based input data specifications are used for the creation of models and for executing simulations [16]. In [17], a tool for rapid layout description and a 3D discrete-event model creation are proposed. In [18], the interface between manufacturing software applications including process planning systems and discrete-event simulation tools was developed. In another solution, a simulation model based on an appropriate input and output data is generated. This model is used for analysis of the sustainability of the manufacturing system [19].

Using the above-described methods and solutions it is possible to reduce both model-preparation time and the cost of simulation experiments; nevertheless, creating very powerful

and flexible supporting tools is particularly difficult. With the increase of their universality, they become very complicated. Moreover, these tools are usually dedicated for specific applications.

Another possible solution is to build a tool that will enable the automatic performance of simple but repetitive and time-consuming activities. This type of activities we do during AGV paths creation. We have to repeat these activities many times, especially if the path network is very large. Therefore, in this paper a method for the automatic creation of bidirectional transportation paths for AGVs is proposed. This method was developed for the Delmia QUEST program.

2. Simple path description

As described above, the proposed method should be easy and simple. Furthermore, the process of preparing input data should be easy to implement. For this reason, the division of the entire transportation area into squares is proposed. In this example, the sides of every square are set to 1 m. Under this assumption, the entire transportation network can be defined in a spreadsheet (Fig. 1).

Fig. 1. The layout of a transportation subsystem in spreadsheet

A single cell corresponds to a 1 x 1 m square. In this example, the number of columns is 30 and the number of rows is 20. Bidirectional roads are marked with 'X' on a green background. Impassable places are marked 'O' on a white background. Parking places for the

AGVs are marked by 'C' on a yellow background. Places on the roads where AGVs can be loaded or unloaded are marked 'S' on a red background. Places where work pieces may be introduced in or out of the transportation subsystem are marked 'E' on a blue background. In this way, a large and complex transportation subsystem can be quickly designed. Projects of transportation layout prepared in this way are saved in the *.csv file format. The part of this file is shown in Fig. 2a. In this file, all signs are separated by semicolon. In the next step, semicolons have to be converted to space signs. Each sign in this file, besides spaces, corresponds to one square. The part of this file with input data is presented in Fig. 2b.

```
E;X;X;O;O;O;E;O;O;O;E;O;O;O;O;O;E;O;O;E;O;O;E;O;O;E;O;E;O;E
O;O;X;X;O;O;X;O;C;O;X;O;O;O;O;O;X;O;O;X;O;O;X;O;O;X;O;X;O;X
O;O;O;X;X;X;X;X;X;X;X;O;O;O;O;O;X;X;X;X;O;O;X;X;O;X;X;X;X;X
E:X:O:X:O:X:O:O:X:O:O:O:O:X:X:X:X:O:X:O:O:O:O:X:X:X:O:O:X:O
```
(a) A part of input data in *.csv file format

```
E X X O O O E O O O E O O O O O E O O E O O E O E O E
O O X X O O X O C O X O O O O O X O O X O O X O X O X
O O O X X X X X X X X O O O O O X X X X O O X X O X X X X X
E X O X O X O O X O O O O X X X X O X O O O O X X X O O X O
```
(b) A part of input data in *.dat file format

Fig. 2. The parts of input data files

The input data in this format can be used for the automatic creation of paths. Any two adjacent squares on the road should be replaced by a single segment in the simulation model. The start point and the end point of each segment should be placed in the centre of adjacent squares.

3. Internal programming languages in QUEST

QUEST is a very popular and advanced tool for discrete-event modelling and simulation; it has developed functionality for 3D model creation. This functionality includes the ability to build models of transportation subsystems based on conveyors or AGVs. Each kind of model can be built using a graphical user interface. In the case of building simple models of transportation subsystems, manual data entry is quite effective. However, when we have to build a large and very complex model, as in this case, the approach described above is ineffective. The process of creating such a complex model can be facilitated through the use of programming languages which are built-in QUEST.

3.1. Simulation control language

The simulation control language (SCL) is a high level procedural language. This enables the construction of logic to control the actions and behaviour of each model object. SCL logic can be used to control the following:

- ▸ routing,
- ▸ processing,
- ▸ queueing,
- ▸ AGV/labour motion,
- ▸ decision point activity,
- ▸ initialisation, termination, simulation,
- ▸ pre- and post-event actions,
- ▸ the behaviour of user defined SCL buttons/macros.

In addition to the applications mentioned above, SCL logic can be used to define several data types, procedures and routines. In this way, the programmer can access different information about each object of the model. SCL provides many standard input and output routines to streams like files, pipes and sockets. Using SCL, the programmer can write procedures for input data file reading.

3.2. Batch control language

The batch control language (BCL) is a command language that is used to control QUEST. BCL commands can be used, inter alia, for the following tasks:
- ▸ reading a model,
- ▸ modifying parameters,
- ▸ running a simulation,
- ▸ interrogating the simulation results,
- ▸ providing visual control.

By using BCL commands, we can provide data to QUEST. What is more important is that it is possible to set model parameters from SCL by calling BCL commands. It is possible to use SCL and BCL language simultaneously; this makes it possible to build procedures for the automatic creation of a model based on input data from a file.

4. Automation of path creation

In the first step, input data was saved in a file named MapOfNetwork.dat. The SCL routines were used to read input data from this file. All this data was stored in the table named MapOfNetwork. A part of the procedure in the SCL language for file reading is shown below.

The part of procedure in SCL

```
open file '../MapOfNetwork.dat' for text input as 1
 for x = 0 to (R_dimension-1) by 1 do
 for y = 0 to (C_dimension-1) by 1 do
 read( #1, MapOfNetwork[x,y])
 endfor
 endfor
close #1
```

In the next step, all segments of AGV paths were created based on this data. All segments joined together then had to be logically connected. In this case, there was a problem in the SCL. The routine which logical connects segments after performing an operation changes the position and orientation of the segments (Fig. 3). Two segments are shown in Fig. 3 – before logical connection (Fig. 3a) and after connection (Fig. 3b).

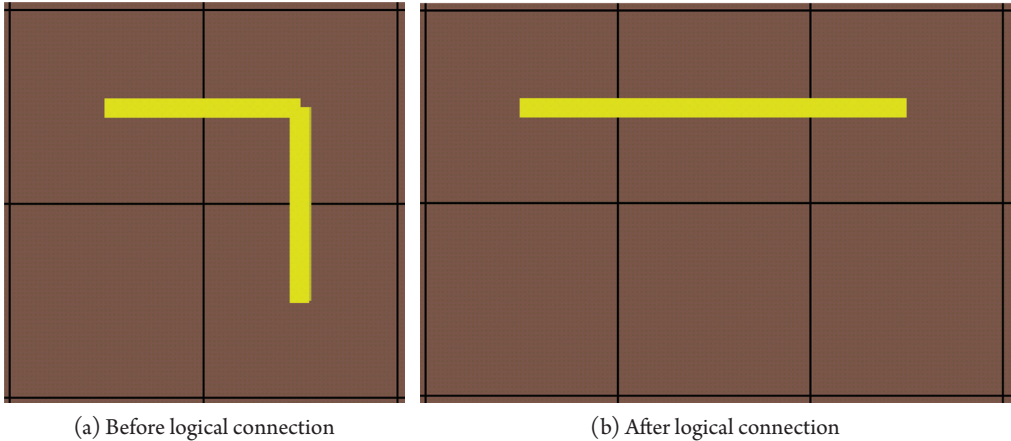| (a) Before logical connection | (b) After logical connection |

Fig. 3. Two segments of road

To solve this problem, a different approach was applied. In the first step, all segments were created in the same starting point. In this case, a BCL command was called from SCL. The part of the SCL procedure which was used for segment creation is shown below.

The part of procedure in SCL

```
...
for x = 0 to (R_dimension-1) by 1 do
 for y = 0 to (C_dimension-1) by 1 do
 if (MapOfNetwork[x,y]<>'O') then
 if (y < C_dimension-1) then
 if (MapOfNetwork[x,y+1]<>'O') then
 if ((MapOfNetwork[x,y+1]=='C') OR
        (MapOfNetwork[x,y+1]=='E'))then
 bcl_status = BCL("CREATE LINEAR SEGMENT FOR
      'AGV_Path_Network' FROM COORD -14.5,9.5,0 TO -13,9.5,0")
...
 endfor
...
```

Following the part of the procedure presented above, appropriate segments were logically connected and again moved to the starting point. The part of the SCL procedure which was used for the connection of segments is shown below.

The part of procedure in SCL

```
...
for y = 0 to (C_dimension-1) by 1 do
 if (MapOfNetwork[x,y]<>'O') then
 ...
 Bcl_Str = "CONNECT SEGMENT
              'AGV_Path_Network_1."+Y1_Str+"'
              FORWARD OUTPUT TO SEGMENT
              'AGV_Path_Network_1."+X1_Str+"'
              REVERSE INPUT"
 bcl_status = BCL(Bcl_Str)
 Bcl_Str = "TRANSLATE SEGMENT
              'AGV_Path_Network_1."+X1_Str+"' TO -14.5,9.5,0"
 bcl_status = BCL(Bcl_Str)

 Bcl_Str = "TRANSLATE SEGMENT
              'AGV_Path_Network_1."+Y1_Str+"' TO -14.5,9.5,0"
 bcl_status = BCL(Bcl_Str)
...
```

Finally, all segments were moved to the destination places and were rotated if necessary. The part of the SCL procedure which was used for the movement and rotation of segments is shown below.

The part of procedure in SCL

```
...
 for x = 0 to (R_dimension-1) by 1 do
 for y = 0 to (C_dimension-1) by 1 do
...
 counter = counter + 1
 if ((MapOfNetwork[x,y]=='C') OR (MapOfNetwork[x,y]=='E'))
 then y1 = 10 - x
 else y1 = 9.5 - x
 endif
 x1 = y - 14.5
 Count_Str = str('%.0f', counter)
 X1_Str = str('%.1f,', x1)
 Y1_Str = str('%.1f,', y1)

 Bcl_Str = "TRANSLATE SEGMENT
              'AGV_Path_Network_1."+Count_Str+"'
              TO "+X1_Str+Y1_Str+"0"
 bcl_status = BCL(Bcl_Str)
 Bcl_Str = "ROTATE SEGMENT
```

```
                ’AGV_Path_Network_1.”+Count_Str+”’
                TO 0,0,-90”
    bcl_status = BCL(Bcl_Str)
 ...
```

An example of the connected segments is presented in Fig. 4. A view of all transportation subsystems is presented in Fig. 5; this corresponds to the layout designed in the spreadsheet shown in Fig. 1. In this way, all segments were appropriately created and connected.
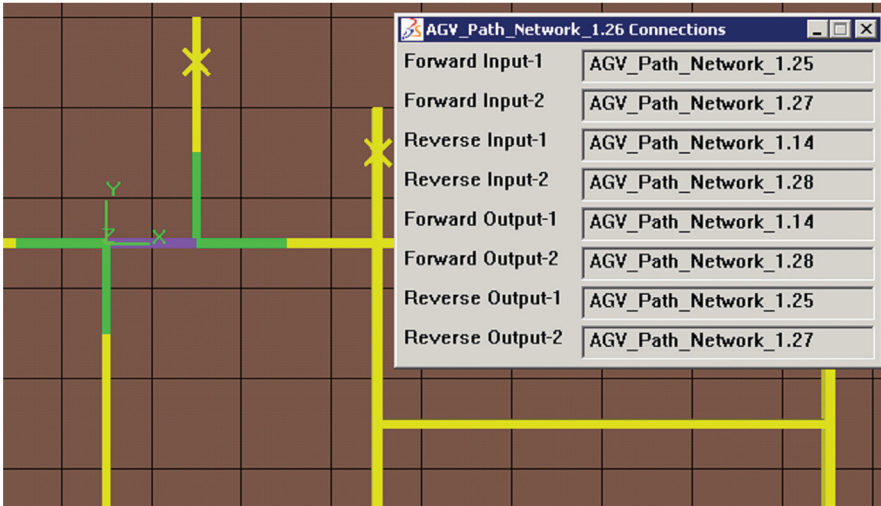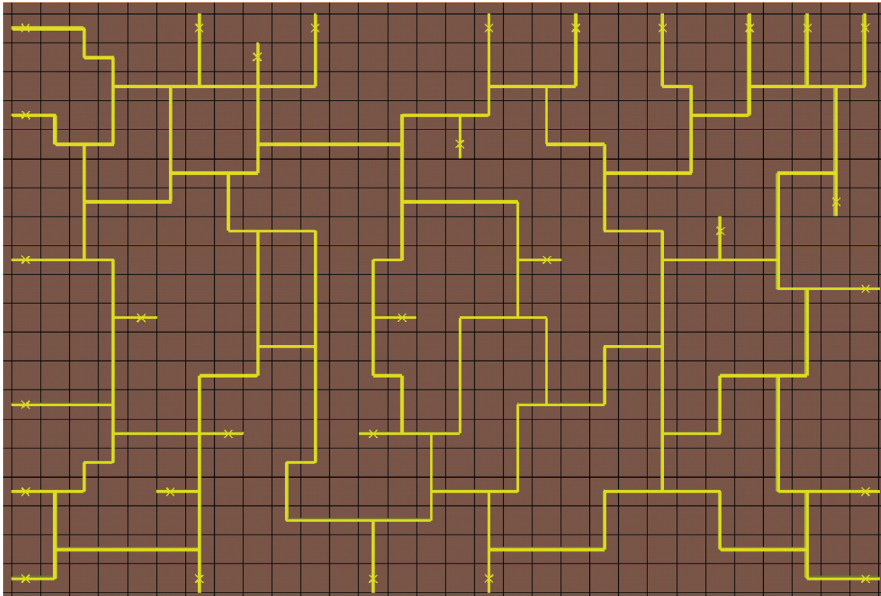

Fig. 4. An example of segment connections

Fig. 5. All segments of a transportation subsystem created in QUEST

5. Final result

Procedures developed in SCL and BCL were implemented into a macro in QUEST. This enables the automatic creation of transportation paths according to the layout designed in a spreadsheet. In the presented example, there are more than 270 segments that have been created and appropriately connected. Doing this manually would be very time consuming. Moreover, it would be very easy to make a mistake.

After all paths creation additional objects were added to the model manually, among others one AGV. Finally, transport tasks were simulated across the transportation paths. In this way, the operation of the transportation subsystem has been tested (Fig. 6).
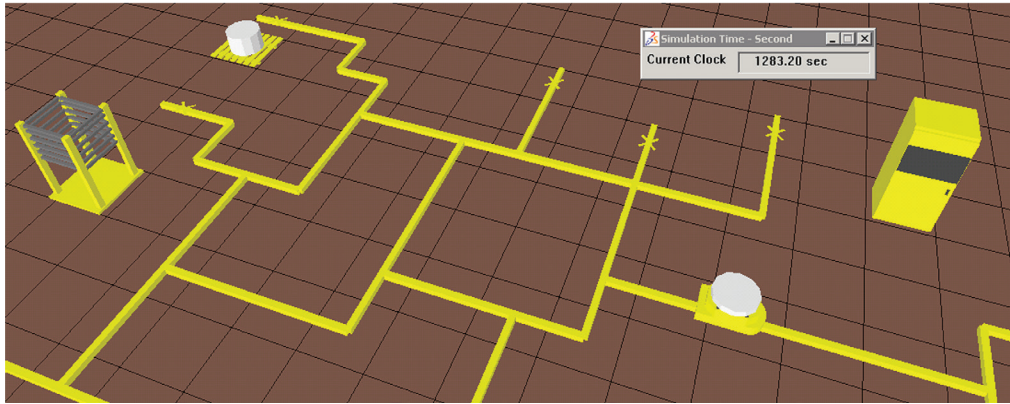

Fig. 6. A 3D view of the simulation process in Delmia QUEST

6. Conclusion

The proposed method is very easy and fast to implement using SCL and BCL in QUEST. The main goal of this approach is to speed up the creation of models. This method is focused on automating repetitive operations and thus avoids a loss of time for simple tasks associated with model building. Using a spreadsheet, we can prepare many different transportation layouts. What is important is that we do not need any specialised tools to achieve this; therefore, we can concentrate on model development or the implementation of a new AGV control strategy. This method can also be applied to build models in other simulation tools, for example, in Arena, based on transportation network defined in a spreadsheet, it can be achieved using Visual Basic.

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