technical transactions
No. 2020/004
architecture and urban planning
sciendo

Retractable roofs in engineering education

Anita Pawlak-Jakubowska
anita.pawlak-jakubowska@polsl.pl | Orcid 0000-0002-6778-9750
Geometry and Engineering Graphics Centre, Silesian University of Technology

Krystyna Romaniak
kroman@pk.edu.pl | Orcid 0000-0002-0132-9225
Faculty of Architecture, Cracow University of Technology

Scientific Editor: Mateusz Gyurkovich, Cracow University of Technology Press
Technical Editor: Aleksandra Urzędowska, Cracow University of Technology Press
Language Editor: Tim Churcher, Big Picture
Typesetting: Anna Basista, Cracow University of Technology Press

Received: November 18, 2019
Accepted: April 2, 2020

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing interests: The authors have declared that no competing interests exist.

Citation: Pawlak-Jakubowska, A., Romaniak, K. (2020). Retractable roofs in engineering education. *Technical Transactions, e2020008*. https://doi.org/10.37704/TechTrans/e2020004

Abstract

This paper presents a proposal for updating and expanding the teaching of technical university students concerning the subject of roofs. Through the analysis of Polish textbooks and teaching studies, a lack of information on retractable roofs was identified. As a consequence, a lecture was prepared to fill this gap and presented to students of the Faculty of Civil Engineering and to teaching staff of the Silesian University of Technology. The main components of the lecture are presented in this article. Furthermore, a discussion was undertaken to analyse the possibilities of incorporating new content (in the form of supplementary material) into the currently run courses as well as into optional classes such as student workshops and optional facultative courses.

Keywords: fixed and retractable roofs, engineering education

1. Introduction

The development of construction technologies and digital tools enables us to design and build works of architecture of increasingly complicated geometry. Examples of these types of projects include designs by Zaha Hadid, such as: the Heydar Aliyev Cultural Center (Baku, Azerbaijan – 2013), the London Aquatics Centre (London, UK – 2012), the Guangzhou Opera House (Guangzhou, China – 2010) and the Bridge Pavilion (Zaragoza, Spain – 2008). In these structures, the border between the walls and the roof becomes blurred. Surprising shapes are obtained in the construction of both fixed and retractable roofs. All are equally fascinating both with their unique geometry and innovative, patented structural solutions.

Roof covers can be discussed from various perspectives. They can be considered through the prism of their geometric shape, technology, or the materials employed in their construction. We can also discuss them as fixed elements of objects, or retractable elements, changing their shape and function. One example of a fixed roof with an interesting geometric form is the roof of the Złote Tarasy building in Warsaw. A different type of structure is the movable brise soleil of the Milwaukee Art Museum by Santiago Calatrava. The two identical wings that form it can be moved in such a way as to imitate the movement of a bird's wings. Control over the temperature and insolation level of the building was increased as a result of this mechanism.

An attempt has been made to update and broaden the knowledge of technical university students regarding the issue of roofs and roofed areas, with a special emphasis given to mobile roofs. The reason behind this decision is the sheer abundance of such types of roofs in the immediate surroundings of our living areas. Garden tents, marquees, canopies, and garden umbrellas all constitute commonly used forms of mobile roofing. Their shape determines the change of the form of the object and its immediate surroundings. The dynamic aspect of these changes needs to be stressed here – completely different looks can be achieved on the basis of whether the roof is open or closed. Architect and designers should consider such structures at the early stages of the architectural designing process. Retractable roofs occurs in such objects as cinemas, swimming pools, theatres, astronomical observatories and sports stadiums. Knowledge of geometry, kinematics and production technology is crucial when designing such types of roofed areas. One has to constantly follow and monitor the latest trends and developments as almost every new realisation is a unique design challenge in terms of both the form and the technology used.

2. Roof research methodology

The paper presents fragments of the lecture prepared for technical universities students. It was developed on the basis of scientific research on roofs. These studies were multi-staged and involved the use of various research methods. The first method was the strategy of logical argumentation (Niezabitowska, 2014: 184–231), according to which, the roofs were analysed from the point of view of their geometry (Pawlak-Jakubowska, 2016; Pawlak-Jakubowska, Romaniak, 2016a: 109–177; Pawlak-Jakubowska, Romaniak, 2016b: 99–107). The studies were performed for two groups of roofs: fixed and retractable. The research tools used at this stage were scientific and didactic studies relating to literature on the subject. Studies in the field of descriptive geometry (Błach, 2009; Grochowski, 2010; Koźniewski, 2007), construction (Buczkowski, 2009), roof architecture (Pottmann, Asperl, Hofer, Kilian, 2007; Roth, 2012; *Roof Design*, 2008), and structure of retractable roofs (Ishii, 2000; Pouangare, Connor, 1990) were analysed. The next stage was the analysis of retractable roofs in terms of kinematics and technology used for their implementation. Case study was used to identify the mechanisms that have been applied for the purpose of roof

https://doi.org/ 10.37705/TechTrans/e2020004

movement (Niezabitowska, 2014: 184–231). Research techniques were based on the analysis of literature (Bögle, Schlaich, Hartz, 2009; Ishii, 2000; Knippers, Cremers, Gabler, Linhard, 2011; Otto, 1972; Pawlak-Jakubowska, 2016; Riberich, 2009: 12–21; Watts, 2014), technical documentation, patents, websites of design companies and the direct observation of the roofs in existing buildings. The final stage of the research was to organise the collected information and present proprietary solutions for retractable roofs by data synthesis. The research method used in this activity was virtual simulation (Niezabitowska, 2014: 184–231). Using appropriate software (AutoCAD and Inventor Professional, Formfinder 5.0), computer models of selected existing roofs were created and the motion of own solutions was simulated. Finally, new roofs proposals were submitted to the Patent Office (Pawlak-Jakubowska, Romaniak, 2019a; 2019b).

3. Lecture on roofs

An analysis of didactic studies performed during scientific research highlighted the lack of any information on retractable roofs. These issues are currently covered as part of a descriptive geometry course conducted at technical universities. The knowledge provided in this field includes information about descriptive drawing and determining the actual size of the roof slopes. Topics discussed are problems of solving flat roofs with the same slope angle, where the corner and basket edges (valley and hip) are determined as was the ridge for the given eaves. In addition, surface classification is given, dividing retractable roofs into rotary and non-rotary.

The lecture was prepared in which the subject matter concerns not only permanent but also retractable roofs. The following sections present the parts of the lecture and discussions on the possibility of including new content for the technical university students education.

3.1. Fixed roofs

The classification of roofs is dependent upon the shape of the roof surfaces and is divided into:

- flat roofs – single-surface (shed) roofs, gable roofs, hip roofs, half-hipped roofs, Dutch gable roofs, Mansard roofs, combination roofs (including Polish-style roofs), pyramid hip roofs, spires, concave or butterfly roofs, saw-tooth roofs;
- curvilinear roofs – conical roofs, oval domes, onion domes, domes, cylindrical roofs, conoidal (saddle) roofs, barrel roofs, vaulted roofs, corrugated roofs. Roofs are often built as fragments of such surfaces.

The contemporary geometric design of roofs goes far beyond this general classification. Technological and material development makes it possible to design roofs using digital tools that feature highly complicated forms and shapes, such as: Catalan's surfaces, pseudospherical surfaces, minimal catenoid or helicoid surfaces, translation surfaces, and complex surfaces (B-Splines and NURBS) for which the shape is difficult to define. Examples of roofs in which these surfaces are used include membrane roofs made from textile fabrics coated in PVC or PTFE. The very slim sheet (membrane) simultaneously plays the role of the roofing and the load-bearing structure. The surfaces most often seen here include Catalan's surfaces (particularly conoids and cylindroids), as well as conical surfaces. Membranes are also defined on the basis of minimal surfaces. In the simplest terms, it is realised by a soap film suspended around a contour that can be of any shape. These types of models can be built during student workshops or laboratory classes, when it is possible to create unique shapes like the aforementioned catenoid or helicoid. These types of classes with students make it possible to increase their creativity in their future design work.

Other forms from the fixed roofs group that feature curvilinear surfaces, which should be included in the knowledge transferred to students, are roofs that are derived from Bezier surfaces, B-Splines or NURBS, which make it possible to obtain highly complex shapes (Fig. 1). The latest computer aided design software is capable of generating NURBS objects. The freedom in the geometric modelling of these surfaces and roofs makes it possible to create interesting solutions, an example of which is Meiso No Mori Kakamigahara, Japan, in which a roof in the shape of a NURBS surface was used.

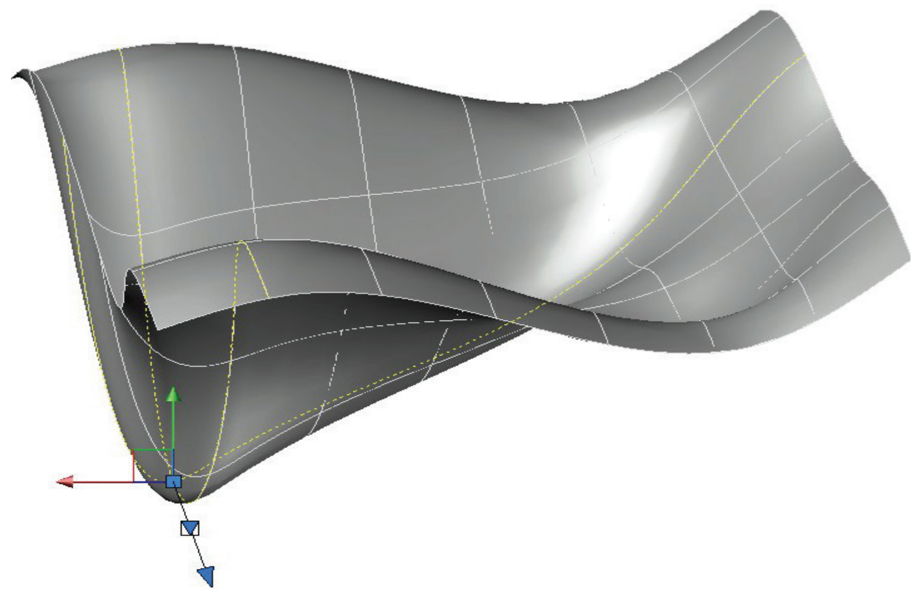


Fig. 1. NURBS surfaces generated by using AutoCAD software (author: Anita Pawlak--Jakubowska)

3.2. Retractable roofs

The distinctive quality of retractable roofs is the change in the form of either part or the entirety of the roof. This is primarily associated with providing shade or protection from atmospheric conditions. It also means changing the function of the building that features this form of roof. "Adaptability and flexibility allow responding to changing requirements in an adequate way. This should also be desirable for artificial structures, but still only few existing buildings are able to react to changing environmental influences, like the few stadiums with a flexible roof or the few movable bridges" (Bögle, Schlaich, Hartz, 2009).

Retractable roofs have been used for many centuries. "Kinetic architectural elements have been integrated into stadia as far back as the days of the Roman Coliseum. The Romans incorporated retractable sun-shades, elevator floors, and trapdoors into the Coliseum for the same reasons that we use kinetic architecture in modern stadia" (Riberich, 2009: 12–21). Some tents (for instance, the tipi of North American Natives) are constructed so that a part of the roof can be opened. This formed an opening which was called the smoke hole. Sunshades, designed to provide shade and cover balconies, terraces and streets, are folded and unfolded either mechanically or manually. They were highly popular in France in the middle of the eighteenth century. Parasols are used to protect against sunlight or rain; the oldest existing image depicting a parasol is dated to the thirteenth century BCE (the Assyrian ruler Assurbanipal is depicted on it riding a cart with a folded parasol with visible structural details).

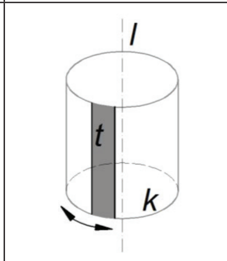
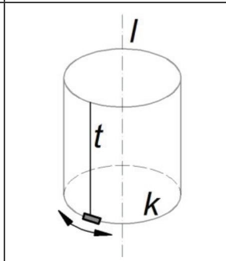
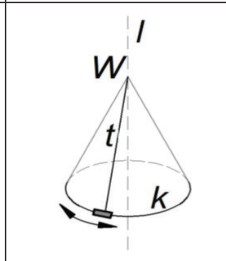
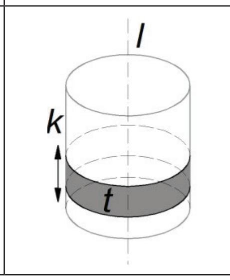
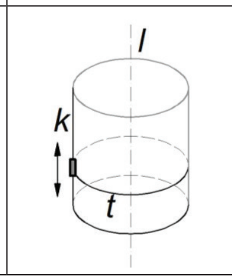
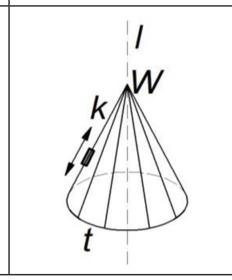
The following classification of retractable roofs was performed on the basis of an analysis of literature and existing solutions. Among the analysed literature, there were, among others, the works of the following authors:

- Frei Otto, who distinguished roofs with stiff panels, dividing them into sliding, folding and rotary roofs (Otto, 1972);
- Chris Pouangare and Jerome Connor, who distinguished stiff structures (sliding, rotary and mixed), folded (sliding, rotary), and deployed – membrane structures (Pouangare, Connor, 1990);
- Kazuo Ishii, who distinguished roofs that made a parallel sliding motion, a circular motion, and that moved up and down (Ishii, 2000).

Ultimately, the division of roofs was formulated using various classification criteria (Pawlak-Jakubowska, 2016; Pawlak-Jakubowska, Romaniak, 2015: 43–52). Due to the manner in which roof panels move, roofs were divided into rotary (Table 1, row 1) and sliding (Table 1, row 2).

On the basis of the technology of their construction, the following roofs were distinguished:

Table 1. Division of surfaces based on the motion performed by roof panels (author: Anita Pawlak-Jakubowska)

TYPE OF MOTION	ROOFS WITH RIGID PANELS – movement of individual panels	ROOFS WITH FLEXIBLE PANELS – movement of the carriage mechanism or support structure	
	CYLINDER	CYLINDER	CONE
1. ROTARY			
2. SLIDING			

- **with rigid panels** – roof panels do not change their shape during movement. Roofs that make the following movements are distinguished: rotary (rotation of plane curve t around the surface axis) – the roof panel moves along a circular path (Fig. 2a); sliding (plane curve t moves along directrix k) – an arch-shaped roof panel moves along a linear path (Fig. 2b).

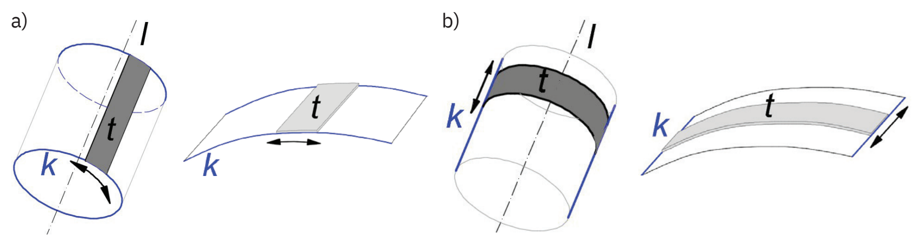


Fig. 2. Two forms of the movement of a roof with stiff panels a) rotary, b) sliding (author: Anita Pawlak-Jakubowska)

- **with flexible panels** – the element being moved is a membrane (fabric), which changes its form during movement, forming the shape intended by the designer when the roof is fully closed. The movement of the roof is performed by the rotation of planar curve t around the surface axis (Fig. 3a). Either a carriage moves along a circular path, tensing the membrane fabric, or planar curve t is moved along surface directrix k (Fig. 3b). In these roofs, the membrane fabric is spread with the use of carriages that move along the surface directrix, which most frequently takes the form of a movable cable, as in the case of the PGE Narodowy Stadium.

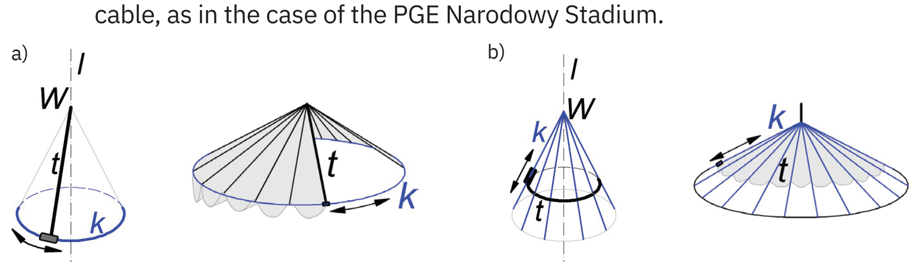


Fig. 3. Two forms of movement of a roof with flexible panels a) circular / rotary, b) sliding (extending along a guideway) (author: Anita Pawlak-Jakubowska)

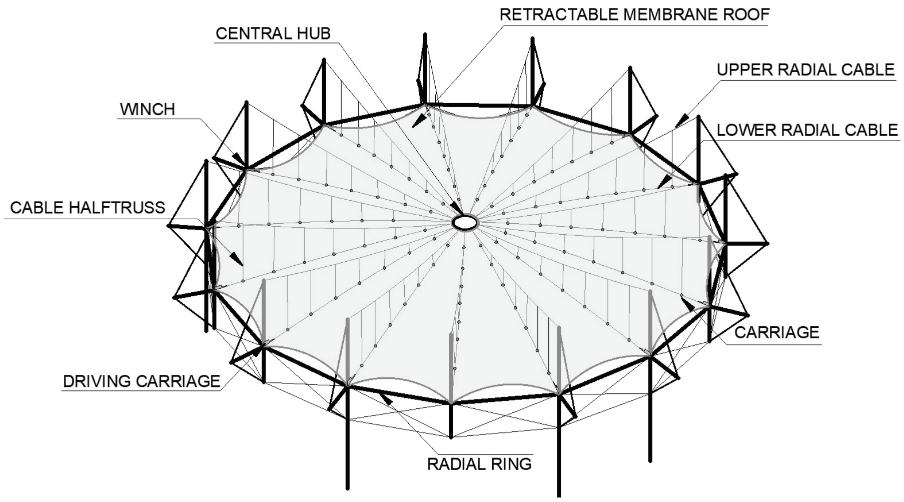


Fig. 4. Scheme of a roof built using the bicycle-wheel system – Kufstein Fortress (Austria) (author: Anita Pawlak-Jakubowska based on (Nunes, 2012))

At present, membrane roofs are often built using the bicycle-wheel system w– it is one of the most advanced lightweight retractable roof structures. Such roofs open towards the centre (Fig. 4), where the folded fabric is stored in a garage.

Examples of projects using the bicycle-wheel system include: the Rothenbaum Tennis Stadium (Germany), the Commerzbank Arena in Frankfurt (Germany), the PGE Narodowy Stadium in Warsaw (Poland). The main elements of this system are radial cables, a tensile internal ring (central hub) and a ompressed external ring (radial ring). Two forms of roofs are featured, one with a single compressed radial ring and two tensile rings, and the other with two compressed radial rings and a single tensile ring. Initially, such roofs had a circular floor plan; however, over time, roofs with an oval or rectangular shape started to be designed, which made it possible to cover larger surfaces, such as football stadiums.

The research work of the authors resulted in the formulation of several solutions of retractable roofs used to cover smaller spaces, such as amphitheatres, courtyards and terraces. Some of these are characterised by the possibility of opening the space underneath the roof (Fig. 5a). Others feature multiple shape modifications – the roof can have a different form every day (Fig. 5b).

a)

b)

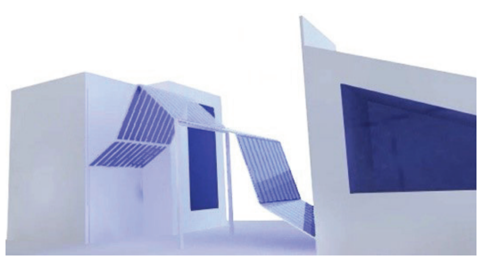


Fig. 5. The authors' solutions of retractable roofs designed using Autodesk Inventor Professional a) roof closed towards the centre, b) roof that features multiple ways in which the shape of its surface can be modified (author: Anita Pawlak-Jakubowska)

4. Discussion

Introducing the new topics mentioned in this paper into students' education is by no means easy and requires a great deal of effort. There are several reasons why it is so difficult, the two most important reasons are as follows:

1. Mobile roofs are structures for which construction requires adequate knowledge from several scientific disciplines. In order to be successfully designed and constructed, close cooperation is necessary between: architects; mechanical, structural and electronic engineers; IT specialists; other technicians from various fields. It often happens that the design

concept constitutes a work of art with later stages being developed by engineers and specialists in other fields.

2. The area of academic research of university staff is not always related to the subjects or courses taught by them at university. For instance, the authors, whose academic interests lie in the area of roofs, need to run courses for students including: *Mathematics*, *Descriptive Geometry, Technical Drawing, General Construction with the Physics of Buildings, Building Materials,* or *Construction Lawe*.

As a result of the above considerations, the authors are planning to introduce new content into their courses conducted at the Faculty of Architecture and Urban Planning and the Faculty of Civil Engineering. Aspects relating to the geometry of roofs (fixed and retractable) will be incorporated into the *Descriptive Geometry* course for the academic year 2019/2020. Additionally, student workshops have been planned which will focus on various forms of roofs and ways of modelling them using computer programs. A crucial tool used for this purpose is Formfinder 5.0, which is available free of charge and is consequently very convenient and popular with students. It allows students to freely create geometrical forms of roofed areas and then suggests technological solutions to be used based on existing objects which have a similar structure. This tool has solutions for both fixed and retractable roofs in its libraries. The preliminary syllabus of the meetings focusing on fixed roofs includes the following topics:

- roofs with flat slopes with different slope angles;
- roofs with curvilinear slopes – Catalan solids (geometrical drawing, model);
- realisation of membranes based on minimal surfaces (physical model, a soap bubble, computer model in, for example, Formfinder 5.0 program);
- roofs derived from Bezier surfaces – B-Spline, NURBS (computer model – 3D modelling).

Issues regarding kinematics and the technology of constructing roofed structures should be complemented with other courses such as *Implementation of Construction Projects, Advanced Materials and Technologies in Construction*, and elective courses (*Review of Famous World's Structures*, *3D Modelling*). This requires cooperation with the academic staff who run such courses. At the Silesian University of Technology, student workshops on membrane roofs have already been organised and, therefore, with the cooperation of the academic staff who run these workshops, the extension of the subjects covered is planned to include the subjects of both fixed and movable roofs. Another way of incorporating these issues into students' education is by offering optional courses. For one such course, under the working title *Moving Structures in Building Industry,* a syllabus has been designed regarding the construction and technology of building moving structures which covers roofs with stiff panels, roofs with flexible panels, bridges, walls, locks and cranes.

The optional classes are planned in the form of regular classes and computer lab classes. Introducing students to the latest trends and research conducted in the area of mobile roofs may encourage some students to further their education with doctoral studies. This type of education gives students the opportunity to conduct academic research and become acquainted with novel solutions in the area of roofs and other mobile structures.

5. Conclusion

Due to the dynamic progress in all areas of life, supplementing lectures with the latest achievements and information on the latest trends appears to be one of the major duties and responsibilities of academic staff in universities. This is especially true in the case of technical universities as the changes in techniques and technology are exceptionally rapid. The presented ideas appears to address these needs. Incorporating the subject of retractable roofs into the education process of future engineers is simply a requirement of our times. The main reasons for choosing this subject is its abundance in our surroundings. Knowledge of geometry, kinematics and technology of constructing such roofs would enable the graduates of technical universities to successfully work as members of specialist teams designing and constructing these most spectacular forms of roofs today. It seems crucial that students get introduced to the subject of retractable roofs at an early stage of their university education.

The material prepared by the authors constitutes a proposal for updating and broadening the current scope of topics discussed and taught within the university curriculum. The lecture which was prepared and presented to the academic staff and students of the Faculty of Civil Engineering of the Silesian University of Technology, became a starting point for further actions (discussed in the Discussion section). Such activities, open to all university students, would be an excellent opportunity for inter-disciplinary actions, which is in line with the vision of educating future architects presented by Celadyn in his work (Celadyn, 2019: 71–75): "New holistic approaches to architectural design have made essential the involvement of many closely – and even loosely – related professionals in the design process. The ever-increasing complexity of problems requires multidisciplinary discussions, which in turn require the development of new platforms to facilitate such discussions". Thus, the presented lecture components constitutes not only supplementary material expanding students' knowledge in particular faculties, but it becomes a pretext for undertaking discussions and multidisciplinary actions.

References

Błach, A. (2009). *Inżynierska geometria wykreślna. Podstawy I zastosowania*. Gliwice: Wydawnictwo Politechniki Śląskiej.

Bögle, A., Schlaich, M., Hartz, C. (2009). Pneumatic structures in motion. In *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium*. Valencia.

Buczkowski, W. (2009). *Budownictwo ogólne*, vol. 4. *Konstrukcje budynków*. Warszawa: Wydawnictwo Arkady.

Celadyn, W. (2019). Controversy over the visions of the architectural profession. *World Transaction on Engineering and Technical Education*, *17*(1), 71–75.

Grochowski, B. (2010). *Geometria wykreślna z perspektywą stosowaną*. Warszawa: Wydawnictwo Naukowe PWN.

Ishii, K. (2000). *Structural Design of Retractable Roof Structures*. Southampton–Boston: WIT Press.

Knippers, J., Cremers, J., Gabler, M., Linhard, J. (2011). *Atlas Kunststoffe und Membranen*. Munich: Detail.

Koźniewski, E. (2007). *Geometria dachów, teoria i zastosowanie*. Białystok: Wydawnictwo Politechniki Białostockiej.

Niezabitowska, E. (2014). *Metody i techniki badawcze w architekturze*. Gliwice: Wydawnictwo Politechniki Śląskiej.

Nunes, E. F. (2012). *Qualitative investigation of the performance of a structural membrane roof project* [Thesis]. Ouro Preto: Universidade Federal De Ouro Preto.

Otto, F. (1972). *IL 5 Convertible Roofs*. Stuttgart: Institute for Lightweight Structures (IL), University of Stuttgart.

Pawlak-Jakubowska, A. (2016). *Ruchome przekrycia – budowa geometryczna, kinematyka, technologia wykonania* [Thesis]. Gliwice: Wydział Budownictwa, Politechnika Śląska.

Pawlak-Jakubowska, A., Romaniak, K. (2015). The architecture of solid and retractable roofs. *Technical Transactions*, 112(22), 43–52.

Pawlak-Jakubowska, A., Romaniak, K. (2016a). Geometria dachów ruchomych. In E. Sroka-Bizoń (Ed.), *Geometria Grafika Komputer* (pp. 109–177). Gliwice: Politechnika Śląska.

Pawlak-Jakubowska, A., Romaniak, K. (2016b). Systematyka dachów stałych w aspekcie ich budowy geometrycznej. In E. Sroka-Bizoń (Ed.), *Geometria Grafika Komputer* (pp. 99–107). Gliwice: Politechnika Śląska.

Pawlak-Jakubowska, A., Romaniak, K. (2019a). Patent. *Modułowy ruchomy dach zawierający panele dachowe*. P.429392.

Pawlak-Jakubowska, A., Romaniak, K. (2019b). Patent. *Modułowy ruchomy dach zawierający połączone obrotowo panele dachowe*. P.429402.

Pottmann, H., Asperl, A., Hofer, M., Kilian, A. (2007). *Architectural Geometry*. Pennsylvania: Bentley University Press.

Pouangare, C., Connor, J. (1990). Classification of structural systems for retractable roofs for stadia, Heavy Movable Structures Movable Bridges Affiliate. In *3rd Biennial Symposium*, November.

Riberich, B. (2009). Retractable stadium roofs and flooring. *Interface*, 12–21.

Roth, M. (2012). *Roof Architecture + Design*. Switzerland: Braun Publishing.

Roof Design (2008). Cologne: DAAB.

Watts, A. (2014). *Modern construction envelopes*. Vienna: Ambra.

Ruchome dachy w inżynierskiej edukacji

Streszczenie

W pracy przedstawiono propozycję uaktualnienia i poszerzenia wiedzy studentów uczelni technicznych na temat dachów. Po przeprowadzonej analizie polskich podręczników i opracowań dydaktycznych zauważono brak informacji na temat zadaszeń ruchomych. Przygotowano zatem wykład uzupełniający tę lukę. Został on przedstawiony studentom Wydziału Budownictwa Politechniki Śląskiej. W pracy przedstawiono główne elementy opracowanego wykładu. Podjęto również dyskusję na temat możliwości włączenia nowych treści (jako uzupełnienie) do prowadzonych obecnie przedmiotów oraz zapoznania z nimi studentów w ramach dodatkowych zajęć (np. warsztatów czy przedmiotu fakultatywnego).

Słowa kluczowe: stałe i ruchome dachy, inżynierska edukacja