CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Civil Engineering

Department of Construction Technology

THE APPLICATION OF INDUSTRIAL ROBOTS IN CONCRETE FORMWORK FABRICATION

Bachelor Thesis

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Annotation

The main aim of this work is to describe design processes, modelling and manufacturing of the formwork for complex concrete structures with the application of several sophisticated software and technologies. Moreover, this work deals with the most widespread problems that have an impact on productivity and efficiency in the construction industry. These problems can be solved by automation and digitation of the construction site. Successful examples of utilizing modern technologies in construction are mentioned as well. The author reviews the contemporary conditions of the Czech construction sector and explains its ability to employ new technologies due to its favourable economic environment.

Key words

Digital fabrication of formwork, robotic hot wire cutter, 3D modelling in construction, industrial robots, EPS formwork, Construction 4.0., KUKA, building engineering, robotic programming language

Anotace

Hlavní cíl této práce je popsání procesů navrhování, modelovaní, výroby a opracovaní bednění pro tvarově složité betonové prvky při aplikaci několika sofistikovaných softwarů a technologií. Také tato práce obsahuje přehled běžných problémů, ovlivňujících produktivitu a efektivitu ve stavebnictví, které mohou být vyřešeny pomocí automatizace a digitalizace staveniště. Dále jsou uvedeny příklady použiti moderních technologií ve stavebnictví. Autor prozkoumává dnešní stav českého stavebnictví a popisuje jeho schopnost uplatnit nové technologie díky příznivému ekonomickému prostředí.

Klíčová slova

Digitální výroba bednění, RHWC metoda, 3D modelování ve stavebnictví, industriální roboty, polystyrenové bednění, Stavebnictví 4.0., KUKA, stavební inženýrství, robotický programovací jazyk

I declare that I worked on my thesis on my own and that I used only the sources listed in the reference list.

Prohlašuji, že jsem bakalářskou práci zpracoval samostatně a použil pouze zdroje uvedené v seznamu literatury.

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Danila Fakhri

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Content

List of abbreviations

3D – Three dimensional

AM – Additive manufacturing

AR – Augmented reality

BIM – Building intelligent model

CAD – Computer aided design

CAM – Computer aided manufacturing

CNC – Computer numerical control

CR – Czech Republic

CSO – Czech statistical office

CZK – Czech Koruna

EPS – Expanded polystyrene

EU – European Union

GDP – Gross domestic product

GFC – Global financial crisis

GVA – Gross value added

IR – Industrial robot

IT – Information technology

KRL – KUKA robotic language

MCDA - Multi-Criteria Decision Analysis

NURBS – Non-Uniform Rational B-Splines

PDF – Portable document format

PVC - Polyvinyl chloride

RHWC – Robotic hot wire cutting

SW - Software

UK – the United Kingdom

US (USA) – the United States of America

Introduction

In one form or another, modern technology has now been introduced into most industries to increase means of productivity, quality and volume. In the construction industry, developments in Information Technology (IT) has had a great influence through the evolution of software applications such as Computer Aided Design (CAD), Building Intelligent Model (BIM), 3D Modelling, Structural Analysis and Project Management Software, among other applications. This has helped to rationalize and simplify design, management and implementation of projects. However, it remains that the introduction of these software applications has had little impact to create significant technological breakthroughs in the actual automation of building practices on site.

Resultantly, the construction industry is often criticized for being slow to innovate in comparison to other industries. Methods of construction have not rapidly evolved since original construction practices, motorized and digitized somewhat, but to date, methods have largely remained fundamentally traditional.

The adoption of Industrial Robots (IR) is able to change this position radically. This automation technique has been applied in many other industries, heavy or otherwise, such as: mechanical engineering, automotive industry, medicine, bioengineering and aerospace. As IR provides precision and rapid production with minimalized human interaction, this can be a determining advantage for its broader introduction in construction as projects increase in design complexity. In large-scale construction, IR can also provide these advantages:

- Simplifying on/off site fabrication of unconventional structural shapes
- Improving fabrication precision and accuracy
- Decreasing quantity of materials, tools and waste
- Reducing production cost
- Reducing the dependency for skilled labour
- Increasing workplace safety
- Increasing productivity and project timelines
- Improve environmental and ecological impact of construction

Also, IR has a great potential to revolutionize the approach to moulding and forming concrete structures. Regarding to progressive development of architecture, which tends to change conventional structure geometry through inspiring from nature and futurism, IR aims at developing technical possibilities in producing and processing building materials. Standard rectangular shapes of concrete structures will change with applying of IR to formwork producing and 3D principle of adding material in layered manner. Construction formwork which typically accounts for 35 % of the total budget for concrete work for standard rectangular structures and 75% of the costs associated with the realization of sophisticated geometry in concrete can be avoided or seriously reduced during building process. [2]

Another prevalent issue in the construction industry is acute shortage of high-skilled employees. Labour productivity has a great influence on a project success; however employers report a shortfall of qualified and skilled labour. Employing low skilled workers cause unpleasant outcomes such as inefficiency, delays and higher expenditure.

Moreover, construction is rated as one of the most health-hazardous industries. Work at heights, damaging noise, asbestos, chemicals, high-voltage electricity and other threatening factors are typical for construction work environment on a building site. Substitution of human labour with IR will decrease number of work related injuries and illnesses, which cause continuing recovery and inability to work. [1]

The change of conventional approaches, also bring about new opportunities for increased energy efficiency and decreased pollution. Innovative ways of processing materials will lead us to great progress in issues of ecology and recycling.

1. A research study on the application of robots to building construction in the Czech Republic and worldwide.

1.1. The Czech Construction Sector analysis and overview

Construction is one of the fundamental industry sectors of the Czech economy and a vital indicator of market development. Nationally, thirteen percent (13%) of employment is in construction, which represents approximately 386 300 people employed. In the last decade, the Czech construction sector reached its peak in the first quarter of 2018, gaining CZK 62 853 Billion in Gross Domestic Product (GDP) rate. Preceding this was the economic transformation in the end of twentieth century, from a unitary planned economy to a market driven one. That was a significant factor that influenced construction and market growth in general. This transformation provided a competitive environment and great growth opportunities. The emergence of domestic construction firms and international companies brought about construction diversity, quantitative and qualitative growth.

The CR accessed to the EU in 2004, this was amidst a seven-year transformation period between years 2000-2006. The accession programme aimed to adopt and harmonize policies to align economic conditions with that, of the other EU member states through a strategic plan. Upon implementation of this strategic plan, substantial development subsidies were obtained. In the period of 2004-2006 the CR initiated 13 programs valued over 1.69 billion Euros. The largest projects were aimed at the development of the transport infrastructure, focused primarily on the reconstruction and building 426 km of highways, valued at CZK 140 million. Moreover, there was the implementation of an environmental project to meet the EU environmental policy standards. A new treatment plant system, for the recycling wastewater, with a 374 km sewerage network connecting 68 810 locations. These projects stimulated the construction industry and sectorial employment, fuelling other construction projects. [28]

The Global Financial Crisis (GFC) of 2008 adversely affected the Czech construction industry. Slowdown in economic growth, real wage doldrums and increased unemployment were characteristic tendencies of the majority EU members. That situation directly affected construction sector by public decreased purchasing power, what caused a reduced demand on a real estate market as a consequence.

The Czech construction industry was resilient to the crisis until 2009 when it reported its third-lowest decrease compared to 2005, of -3.7% (from 9.9% to 6.2%). Better results were only reported by Switzerland and Poland. In summer 2010, the situation in the Czech construction industry dramatically worsened, a decrease of -7.6% in 2010 was the sixth highest, with the earliest expectations of an upturn to only be in 2013 or 2014. [11]

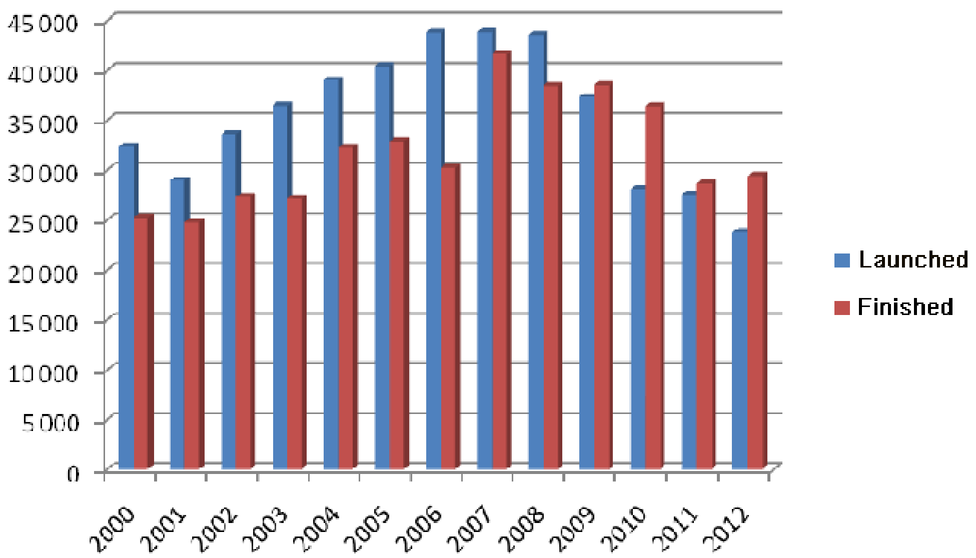


Fig.1 Residential housing development in the CR (housing projects are represented by No. of apartment). Source: [9]

The long term slump in construction recovered after 2013 after interest rates and lending policies were rationalized. The first year of growth increasing the Czech Construction Confidence Index (CCI) by 24.3 points was in 2014. The growth was stimulated by an increase in budgets and better defined strategies adopted by the government between 2013-2014. These measures were expected to continue to stimulate growth for the follow-on years. The recovery was mainly driven by governmental strategy to further develop transport infrastructure and to increase energy efficiency and improve housing quality of prefab residences which was built before 1994 all across the country, through a residential reconstruction initiative. [28]

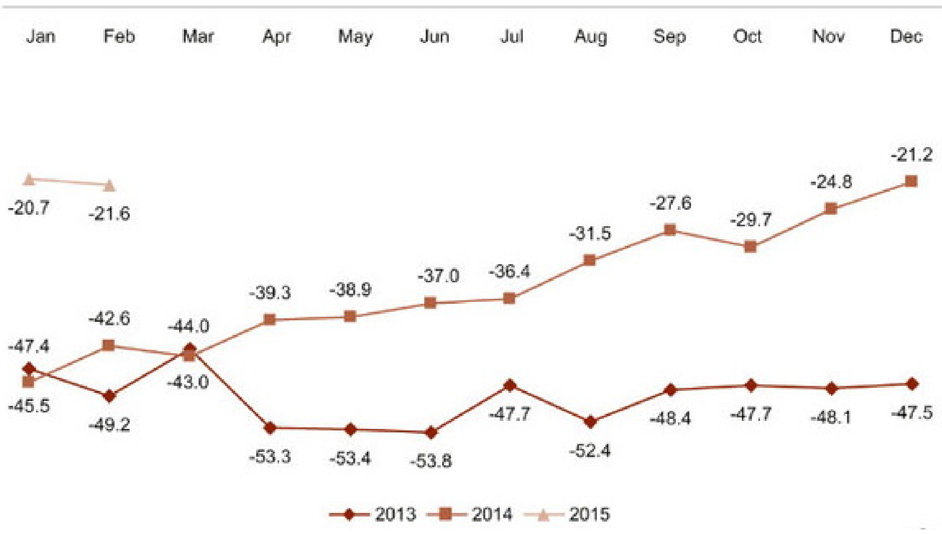


Fig.2 Construction confidence indicator in the Czech Republic, 2013 – 2015
Source: [28]

It was revealed in the 84th Euroconstruct conference, that the conditions of the Czech construction sector were expected to maintain its course and to improve in following years. [23] As it was mentioned in introduction, construction GDP peaked at the beginning of the year 2018. This fact suggests an optimistic environment for development and contributing to construction. In the fourth quarter of 2017 annual growth of started housing projects was 5.4%, which equals to 8,182 flats. [24]

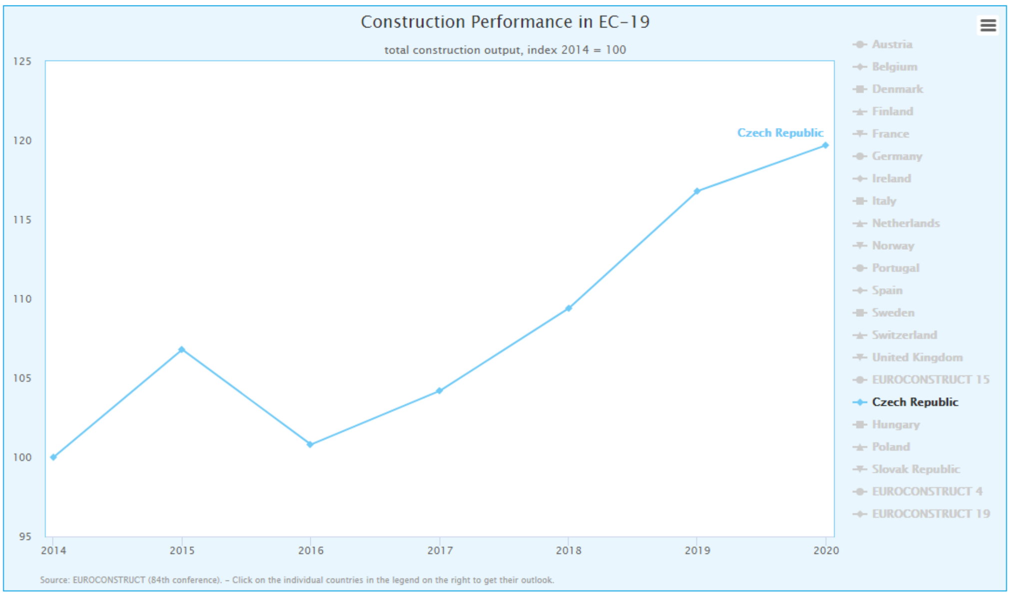


Fig.3 Construction performance of the Czech Republic. Source:[23]

The construction industry generates jobs for a large number of people and remains a popular industry to be employed in. The European construction sector is one of the leading industrial employers, representing 7.5% of the total European employment and 28.1% of industrial employment in the EU. Also the European construction sector comprises roughly of 1.9 million construction firms, 97% of which have fewer than 20 workers and 93% fewer than 10. The biggest employers are Germany (1.96 million), France (1.77 million) and Italy (1.55 million). [13] In the CR local employment in the construction sector has been declining over the long-term, this has caused annual salary increases. Workers in construction have become a very valuable resource; with each company trying to retain employees and keeping them satisfied by creating the better working conditions.

Tab.1 Annual growth of workers employed and their approximate wage in CR. Source: [24]

Year	*Annual growth of workers employed*	*Approximate wage (Gross pay)*
2013	-8.70%	29 042 Kč
2014	-2.50%	29 827 Kč
2015	-1.60%	31 730 Kč
2016	-2.90%	33 012 Kč
2017	-0.50%	34 478 Kč

Summarizing and analysing vital indicators of the Czech construction sector it appears that it is very positive for adopting innovative technologies.

1.2. Relevance of implementation industry 4.0 concept in construction

1.2.1. Construction 4.0

The first industrial revolution started with the invention of steam engine in 1760. It changed transportation and manufacturing radically and allowed to move forward to transform other industries such as agriculture, steel and textile. The second industrial revolution was in the beginning of 20th century with the invention of the internal combustion engine, which paved the way for growth of mass production, it fostered electricity production and drove a new oil-based economy. The third industrial revolution started in 1960's. It began with the implementation of IT and electronics to automation production. It is often referred to as the digital for computer revolution because it led to the introduction of personal computers in the 1980's and later, the Internet in the 1990's. The fourth industrial revolution is happening now by involving CAD (computer aided design), 3D printing and modelling in mass production, utilization of additive manufacturing to make production more precise and rapid.

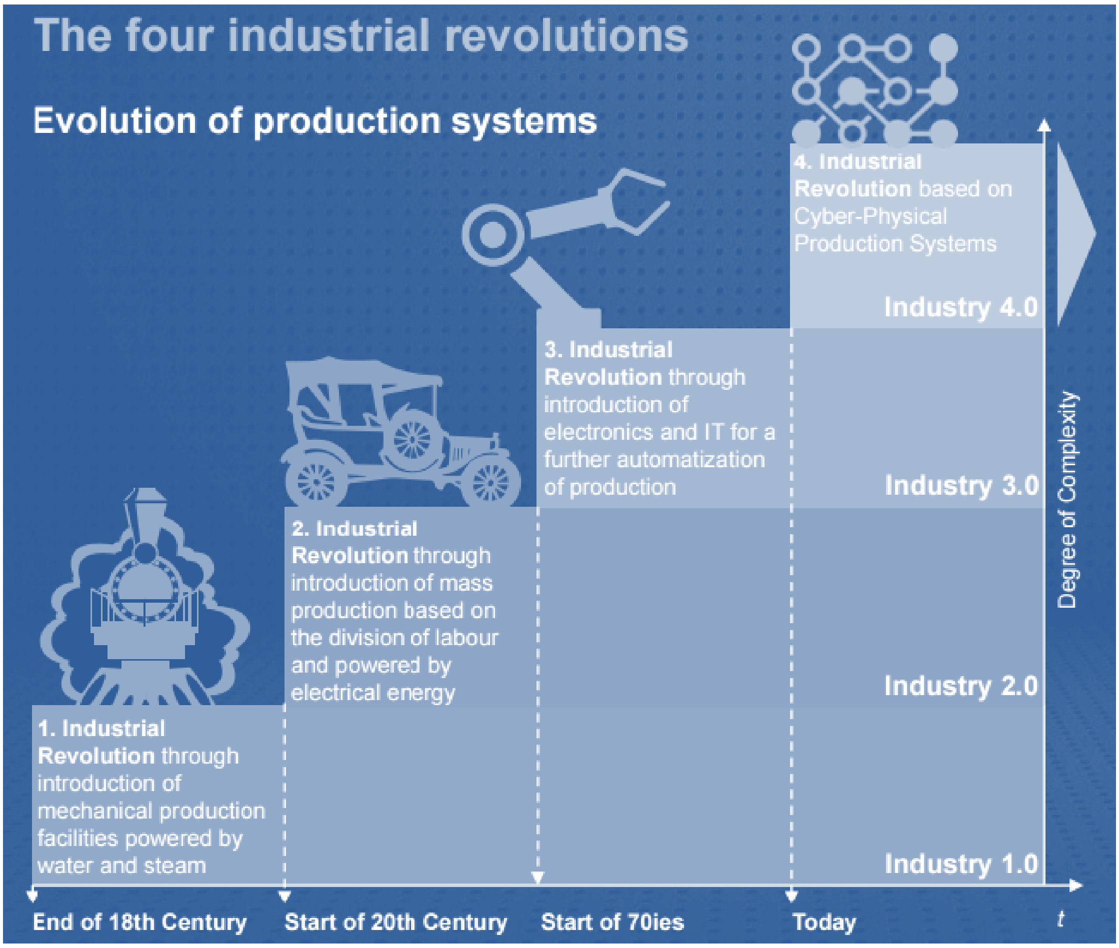


Fig.4 Industrial revolutions. Source: [12]

Construction 4.0 mainly concerns the application of new technologies that have already improved several industries such as the automotive, mechanical engineering, aerospace and pharmaceutical among others. The main aim of construction 4.0 is to transform the industry by introducing advances in:

- Digital technology
- Materials technology
- Construction automation technology

Digital technology

The key tool to transform designing, planning and budgeting is 5D BIM. The "digital twin" of an actual construction project. This essentially being, 3D CAD with added scheduling and cost layers, which provides an effectively consolidated and visualized platform to improve project management, supervision and implementation.

The coupling of BIM with augmented and virtual reality will also provide digital interaction between offices and the work site. Replacing paper-heavy processes with simple and intuitive apps that provide a real-time communication among the work streams, to find solutions and make effective decisions rapidly. These apps can be used on tablet devices, which increase mobility in logistics, management, supervision, inventory and tracking.

Surveying is the next field to be enhanced by Construction 4.0. Labour-intensive devices for electronic measurement are tending to be replaced by photogrammetry and satellite positioning systems. Laser scanners and optics detect millions of points converting them to useful data. Processing of points is making real to transmit implemented buildings and structures to high-resolution images and 3D models. Internet of things (IoT) is a system composed of wireless technologies, internet, electromechanical systems and micro-services.

Machines and devices are connecting to each other through network without human interaction, collecting and saving data to the cloud. Machine to machine communication (M2M) captures real-time data from equipment and workers to provide precise information to contractors, stakeholders, suppliers and managers. It helps to monitor supply chain, to track the implementation of projects and analyse productivity. Applying advanced analysis on these data will provide great improvement in all spheres of construction. [3]

Advanced materials

The materials used in construction have a big impact on the productivity of the industry. A drive toward lighter-weight, more flexible materials facilitates both logistics and execution on-site. Increasing pressure of green construction is also encouraging the development of new construction materials. As concrete has become the leading material used in large construction projects, even marginal improvements in its advances will have a major impact on the industry. Primarily advances in weight, flexibility and versatility of concrete such as self-consolidating and self-compacting concrete. In the longer term, more radical adaptations, particularly to concrete are under development.

The industry is also experimenting with carbon nanotubes as a strong, very lightweight alternative to conventional reinforcement; new polymers and plastics are also having an impact on more repetetive applications. In, Rotterdam city officials have approved a pilot project that uses recycled plastics to form modular road sections that would replace traditional asphalt construction and potentially last more than 50 years.

Finally, a number of brick substitutes made of natural materials are being developed, including fly-ash bricks made from volcanic ash, sand, lime, and gypsum.[3]

Construction automation technology

Additive Manufacturing in construction is still in the early stage, however it is now possible to print sub-models or even complete concrete structures. [3] The technology enables the production of purpose-built shapes that cannot be produced by any other method; it promises productivity gains of up to 80% for some applications, together with an important reduction in waste. Construction time for some buildings could be shortened from weeks to hours, and customized components could be provided at much lower cost. [12]

Autonomous heavy machinery has many benefits, including higher utilization ratios and reduction in operator costs. Some machinery companies have already brought a vast fleet of autonomous excavators, dump trucks and bulldozers. Coupled with the intelligent machine control technology and advances in drone surveying, machines are now capable of conducting pre-foundation work autonomously. Robotics has had enhanced the productivity in many sectors and it could do the same in construction. Highly repeatable elements of construction such as bricklaying and concrete paving have already started to incorporate it. [3]

1.2.2. Global shortage of skilled labour in Construction

The labour cost in construction accounts for 30-50% of the total cost of construction projects. [3] The lack of high-skilled workers was mainly caused by the Global Financial Crisis in 2008. In the US, after the economical breakdown, approximately two million construction workers lost their jobs and were forced into informal and vulnerable employment elsewhere. Around 200 000 jobs in construction are still vacant nowadays due to labour shortage. [26] In the UK, about one fifth of all vacancies in the wider construction sector remain and are hard to fill, employers cannot recruit staff with the right skills, qualifications and experience. More than half (53%) of the employers in the UK construction contracting sector reported skills shortages in professional occupations. Employers report that these shortages would lead to increased costs and inefficiency.

Construction, like many other sectors, has a strong hierarchical structure, with skilled and highly qualified workers; their main duties are to design, plan, control and manage. In general, the quality of the on-site labour workforce is difficult to ensure, which plays a crucial role for timelines and quality.

The level of performance of skilled workers has been seen to be a major factor which contributes toward project productivity. Employing low skilled workers cause undesirable outcomes such as inefficiency, delays and higher expenditure. However, some areas of the world have turned to informal or unskilled labour to fill the labour gap, which does not seems to be the right way to solve this problem. [15]

"Vacancy rates in narrow construction and real estate activities in the EU increased from 0.9% to 1.1% and from 1.0% to 1.2% over 2009-2015, respectively, indicating that the mismatch between the supply and demand of labour in the construction sector is increasing and that the sector is experiencing a skill shortage. There is a lack of technicians, namely electricians and machine operators, as well as other occupations, such as roofers, carpenters and stonemasons, often due to unattractive working conditions, mobility, and immigration trends". [14]

1.2.3. Health risks in construction

The construction industry still remains as one of the industry associated with health and safety hazards. According to "European Agency for Safety and Health at Work" Construction workers are killed, injured or suffer ill-health more than in any other industry.

In Europe, every year more than 1000 workers are killed and over 800 000 workers are injured. Others are suffering ill-health, such as musculoskeletal disorders, dermatitis and asbestos exposure. [16] There are many life-threating factors which are always appearing during site work such as: working at height, high-voltage electricity, arm vibration syndrome, noise, fire, asbestos exposure, respiratory hazards, heat exposure, slips and falls, collapsing trenches/scaffolding.

The most frequent reason of fatalities in construction belongs to falls. Safety coordinators participate in all phases of construction work to protect workers and to prevent them from various dangers. However, workers still regularly ignore safety rules, which causes serious life-damaging incidents.

Introducing new robotic technologies on a work-site will reduce the level of incidents and injuries. Where possible the replacement of human interaction through this type of automation will help employers to avoid these health and in conjunction, benefit from the associated savings on the copious regulated health and safety protection and precautionary costs.

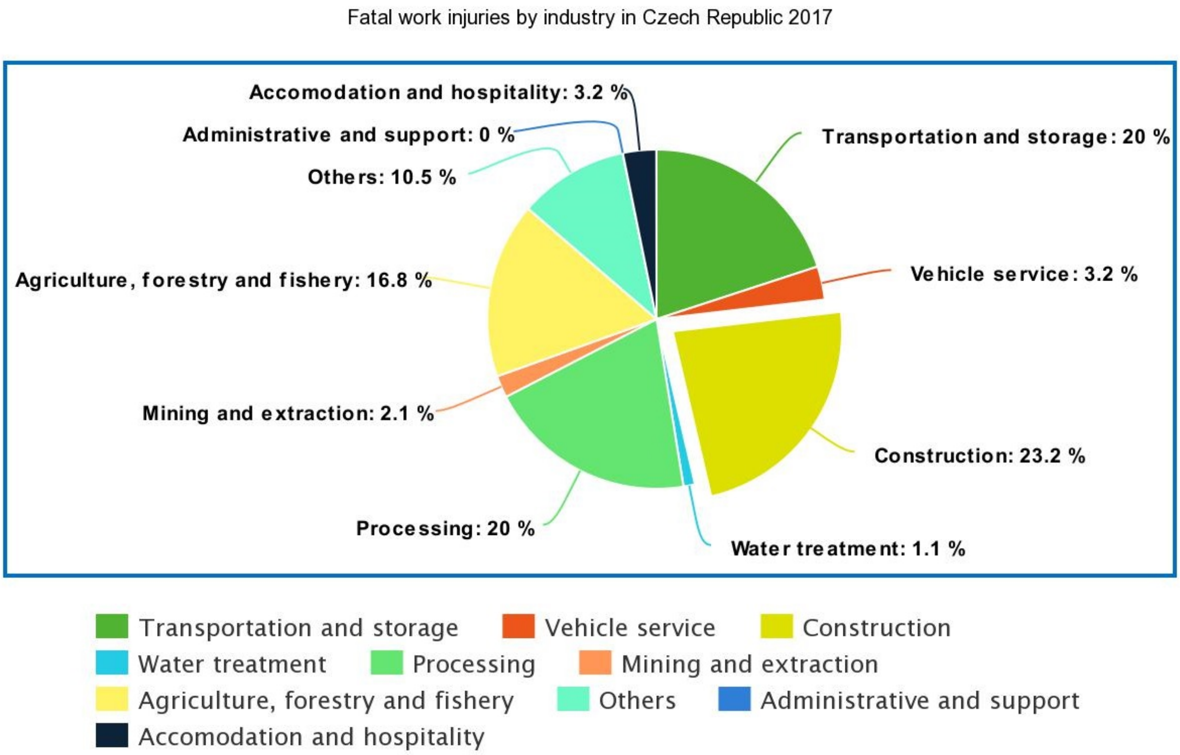


Fig.5 Fatal work injuries in Czech Republic in 2017. Source: [24]

1.2.4. Automation of construction site processes

In comparison with other industries, construction is regarded as a stagnant-productive and low-innovative one. Whilst other industries are creating emphasis to modernize their processes of manufacturing, construction remains one of the most stagnant industries in the world that uses many of the same methods first invented in past centuries. As a result, declines in productivity and need to be improved by adopting new technologies.

Digitalization and innovative technologies are reaching market slowly. Many innovative solutions have already been applied on a smaller scale, however the construction industry still needs more large-scale applications and better ways to impact technological developments. Adopting new technologies such as: drones, robotics, augmented reality, 3D scanning and printing, advanced building materials and autonomous equipment will enhance productivity, quality and safety.

Although every construction project is unique, there are number of repetitive processes which remain the same for any building project. These cyclical processes may differ by quantity, period of time and cost. However, implementing new technologies to change and to improve these processes will have desirable impact on all project components.

There are many reasons why construction remains a low-innovation sector. According to MGI's digitalization index, construction sector in Europe is in the last position in comparison with other industries. The main reason is that construction companies really underinvest in digitalization and technology. In 2006, 70% of construction firms dedicated 1% of their revenue to technology. [3] Between 1991 and 2007, German construction sector invested 0.7% of Gross Value Added (GVA) in digital assets annually. In comparison, investment in digital innovations in the manufacturing sector and financial intermediation was 1.8% and 4.3% of sectors GVA respectively. The US construction sector invested 1.5%, manufacturing sector 3.3% and financial intermediation 5.7%. [3]

There are some examples in the construction sector of the use of digital technologies having had substantial productivity benefits. In a tunnel project in the United States that involved almost 600 vendors, the contractor put in place a single platform solution for bidding, tendering, and contract management. This saved the team more than 20 hours of staff time per week, cut down the time to generate reports by 75 percent, and sped up document transmittals by 90 percent. In another case, a $5 billion rail project saved more than $110 million and boosted productivity by using automated work flows for reviews and approvals. [3]

Productivity growth is highly dependent on level of technological progress and digitalization. One of the best examples of how technologies are influencing manufacturing is The Boeing Company who designs, manufactures and sells airplanes. In partnership with Iowa State University, Boeing decided to improve assembly of wings, which is technically-difficult and complex process, through applying of augmented reality (AR) during manufacturing. Manufacturing and assembling of wing consists of 50 steps with 30 different components. The group of workers were broken up into three groups; the first group used a desktop through typical PDF plans, the second group had that same PDF on a tablet, the third group was given an AR based tablet where plans and visualizations were meshed over the real objects. Finally, the third group showed the best results by median number of errors less than one during first trial of manufacturing and assembling. During the second trial there were zero defects found. [22]

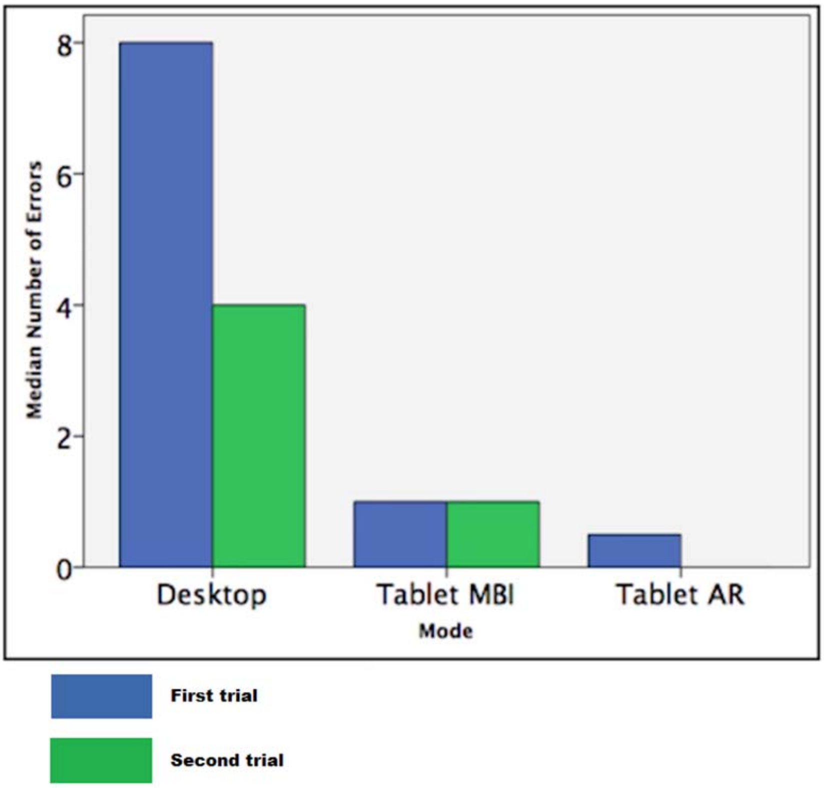


Fig.6 Median number of errors during wing assembly. Source: [22]

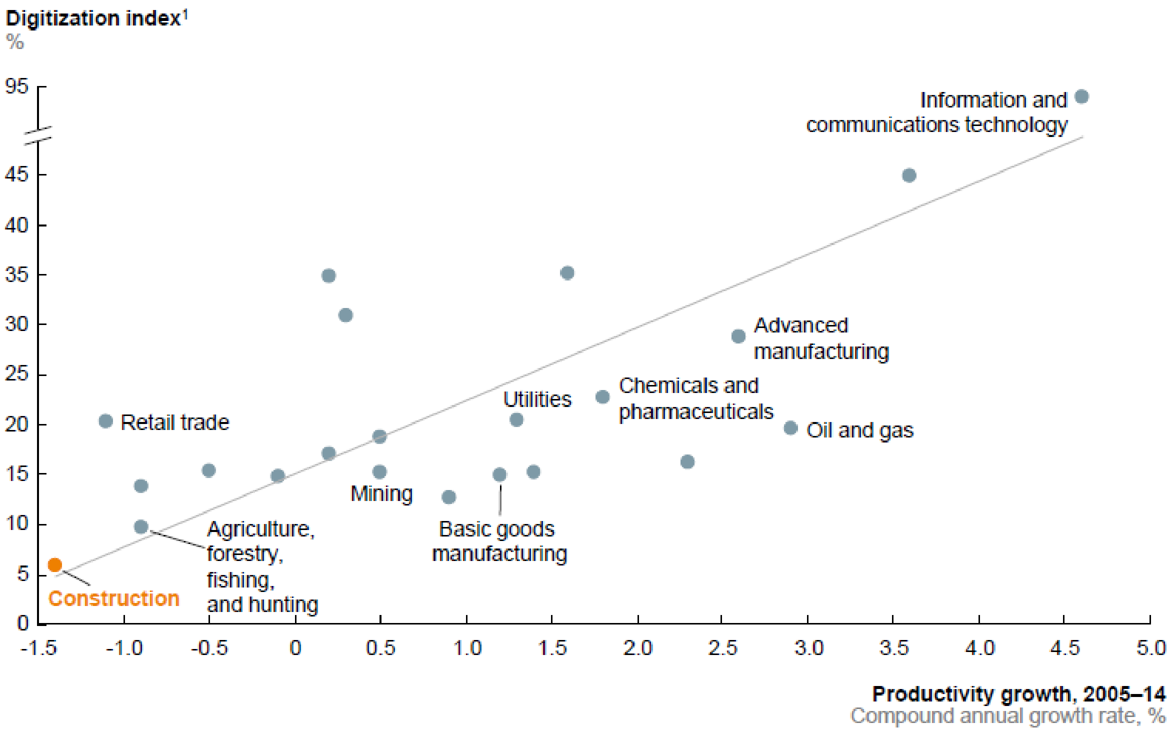


Fig.7 Rate of industrial productivity growth regarding to digitalization index. Source: [3]

1.2.5. Industrial robots

In 1969, the world's first industrial robot was designed at Stanford University by Victor Scheinman. Its name was the "Stanford arm" and it had six degrees of freedom. Today the world's largest industrial robot companies are KUKA (Germany), ABB (Switzerland), FANUC (Japan) and Yakasawa Electric (Japan). The sum of their sales volume of industrial robots accounts for half of the total market. According to the forecast of IFR in its 2015 statistics report "World Robotics 2015", the sales volume of industrial robots in the world from 2016 to 2018 will grow at an average annual rate of approximately 15%. [4] There is an increase in the demand for precision and productivity provided by robots due to the complexity of products today. Nowadays, industrial robots have occupied virtually all sectors of manufacturing: mechanical engineering, automotive industry, pharmacy, metal, aerospace, electronics and many others.

Construction is a highly unautomated industry where human labour is the main factor of productivity. Utilizing industrial robots in construction brings new possibilities in development of productivity, complexity, precision and safety. Making a whole construction site fully automated with minimal human involvement is still far away. However, robots are able to improve manufacturing and production of building components through applying of

Computer Aided Manufacture (CAM) principles. Producing complex elements and even structures through CAM is taking place worldwide. The utilization robotics in construction has become very wide for a variety of applications and it is still expanding. Here are some the most developed applications:

- **Bricklaying**

The most known historical building element – the brick, can now be laid by industrial robot, and there are several reasons why. First is the precision; bricks can have not only the purpose of being a single building element of the structure, but also an aesthetic one. Laying bricks in a specific manner with a high precision can add an artistic pattern to a typical structure.

One of the examples of applying robotics for architectural purposes took place in Fläsch, Switzerland in 2006. The object was a Gantenbein vineyard's service building, consisting of a large fermentation room for processing grapes, a cellar dug into the ground for storing the wine barrels, and a roof terrace for wine tastings and receptions. The masonry of the vineyard's façade looks like an enormous basket filled with grapes. The robotic production method that was developed at the ETH (Swiss Federal Institute of Technology in Zurich) which enabled to lay each one of the 20,000 bricks precisely according to programmed parameters—at the desired angle and at the exact prescribed intervals.

This allowed the design and construction of each wall to possess the desired light and air permeability, whilst creating an external pattern that covers the entire building façades. According to the angle at which the bricks were set, the individual bricks each reflect light differently and thus take on different degrees of brightness. The façade was divided into 72 elements of 3.33 meters and 4.75 meters of length and 1.48 meters of height. Each element was built up on a concrete lintel for ease of transportation.[5]

Fig.8 Vineyard façade. Source: [5]

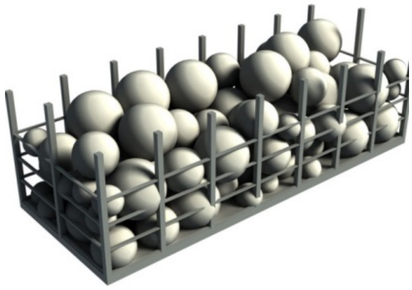


Fig.9 3D model of basket. Source: [5]

Fig.10 Robotical bricklaying Source: [5]

Secondly is productivity and mobility; bricklaying robots are now been deployed on construction sites in the USA and Australia. The need in automation of bricklaying is mainly caused by a labour shortage. The “SAM 100”, which is short for “Semi-Automated Mason”, is produced by Construction Robotics co. can place between 300 and 400 bricks per hour, compared to a worker which can only lay around 60 to 75 bricks per hour(Construction robotics). In the same time, the “SAM 100” is still doesn’t operate completely autonomously. Through an operator, its purpose is rather in support, to help the masons with lifting and laying heavy bricks with mortar in repeatable manner. Approximate price for SAM 100 is $500 000. [20]

Fig.11 Bricklaying by „SAM“. Source: [20]

One more prominent representative of masonry construction robots is the “Hadrian X” designed by an Australian company “Fast Brick Construction”. The company states that applying of the “Fastbrick Wall” system allows to speed-up bricklaying, up to 1000 bricks per hour, which includes the usage of optimized blocks sized at 500x250x250 mm. Its software exports 3D models of a house into data for operation; the “Hadrian X” prints the structure like a 3D printer by cutting the bricks for plumbing and electrical services. The system is fully automated and able to work nonstop. Today, “Hadrian X” has been used to build 10 houses I the outdoors. The Hadrian X costs approximately AUD$2 000 000. [21]

Fig.12 Hadrian X. Source: [21]

- **Concrete printing**

The technology of concrete printing has more questions than answers, to date. Current examples have not yet progressed in the use of real concrete. In most cases printed material is the cement mortar because of the absence of gravel. Unlike the conventional approach of casting concrete into formwork, 3D printing combines digital technology and use of new material technologies that allows freeform construction, without the use of expensive formwork. The formwork typically accounts for 35-40% of a total budget for concrete work. Freeform construction will enhance architectural expression, especially concerning production costs of the structural component, as it will not be dependent on the shape; thus, providing much needed freedom of the rectilinear designs. The extrusion-based technique is the method which extrudes cementitious material from a nozzle mounted on a gantry, crane or a 6-axis robotic arm to print a structure layer by layer. This technique has been aimed at on-site construction applications such as large-scale building components with complex geometries, and has a great potential to make a significant contribution to the construction industry. [6]

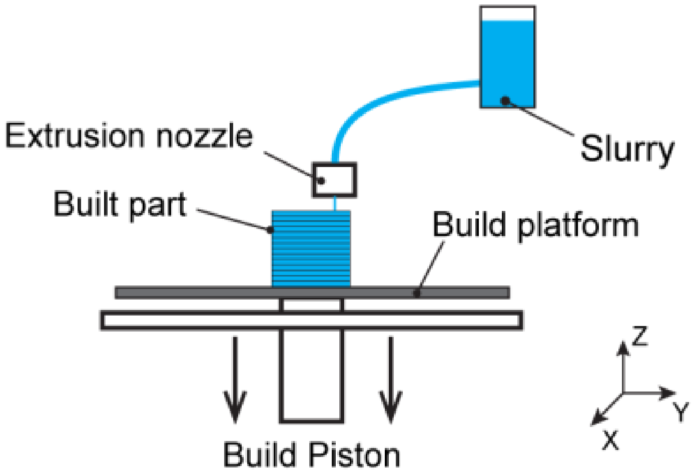


Fig.13 Progress of 3D concrete printing. Source: [6]

The playground roof of a school in Aix-en-Provence, France is supported by 4m high posts, designed by architect Marc Dalibard in 2016. The post was made in two parts: its envelope and concrete core. After the final geometry was designed by topological optimization, it was divided in four elements for prefabrication. The envelope of the post is a lost formwork which was 3D-printed a then filled with concrete, then assembled on the construction site. The post was completed with a marble finish to create smooth surface and to cover up seams. [18]

Fig.14 Concrete post.

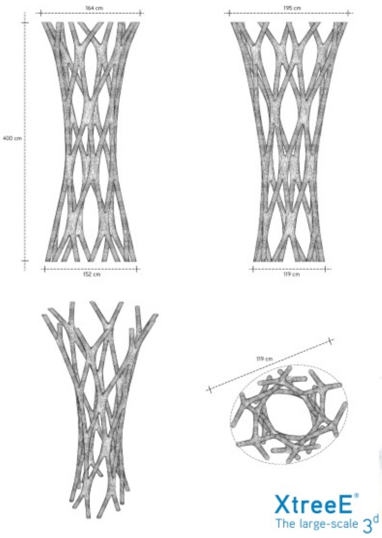


Fig.15 Blueprint of post.

Fig.16 Manufacturing of post.

Source: [18]

- **Producing the formwork**

Production of concrete formwork utilizing industrial robots is possible in several ways with diverse materials. However, the most promising ones are the Robotic Hot Wire Cutting (RHWC) method and Computer Numerical Control (CNC) milling. Expanded Polystyrene (EPS) is a material that can be used as insulation in construction and for forming and shaping of concrete as well. Many complex concrete shapes can be created with polystyrene blocks efficiently. The EPS formwork can be applied to any type of load-bearing structure. It has already been used in several highly praised projects in Europe and Asia that have received awards in architecture. The EPS formwork blocks are practical, economic and efficient. Being lightweight they are usually easy to install, and are often more time and cost effective than their timber and steel alternatives. Additionally, another advantage is the ability to fully recycle all the waste that has been generated during the processing and shaping of the formwork. The waste chunks are cut into small pieces and then shredded. The same principle works with the used formwork. The formwork is disposable; as there is no need for reusing it due to its unique shapes. One of the first full-scale cases for using industrial robots in producing of EPS formwork was in 2018 in Prague, Czech Republic. The column's capitel of the gas station roof in Liben was shaped with the application of CNC milled formwork by KM robots. The formwork for one capitel consisted of three EPS blocks that were milled in a round and transverse manner with a KUKA KR210 robot. Three EPS blocks with a total dimensions 3.0x3.0x1.2m were bound together with a strap and then placed in front of the robot. The total time of milling took 2 days. The formwork then was coated and installed on a falsework provided by DOKA. [19]

Fig.17 Concrete colum.
Source: [19]

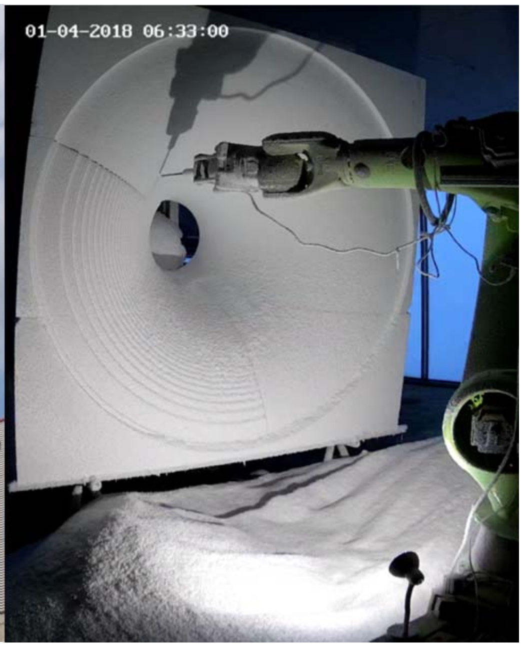


Fig.18 EPS milling.
Source: [19]

2. Modern productive techniques for formwork fabrication

2.1. Modern architectural demands

Architecture is one of the oldest arts in the history of mankind that directly reflects customs, traditions, politics, society and economics. As in any art, architecture has a rich history of its development and transformation supported by science, time and population. For centuries architecture has been an evolving field for many artists who invented and developed new architectonical styles. In the second half of the 20th century, a philosophy emerged from the term deconstruction that changed the concepts of many intellectuals, theorists and academics, and impacted many creative domains, especially architecture.

The term "deconstructivism" was first used at the end of the 1980s to denote an architectural style that embodied the works of architects from all over the world. Deconstructivism has radically changed well-established approach to building design, especially its envelope. It may have seemed to be fragmented and lacking any visual logic, or being too provocative or futuristic.

In 1988 an exhibition at the Museum of Modern Art in New York, organized by Philip Johnson and Mark Wigely, showcased the works of Peter Eisenman, Daniel Libeskid, Frank Gehry and Zaha Hadid among others. For the exhibition, architect Mark Wigely chose projects that disrupted thoughts and dismantled the idea of total and pure form, he categorized the projects as deconstructive architecture.

Deconstructive philosophy in architecture attempts to dismantle all the Euclidian geometric principles that include compatibility, unity and stability also distorting the relation between the interior and exterior. Deconstructivism in buildings is about the use of unique objects which requires responsible decision making and to find specific design solutions for their implementation. Initially, it seemed impossible to implement and calculate loads in such complex objects and to precisely manufacture components with the required materials. [7]

Complex geometric shapes are common for the deconstructivism style. Non-standard shapes have to be parameterized for the further manufacturing of building components and elements. For parameterization and transforming freehand architectural sketches and drawings into 3D models and blueprints, NURBS (Non-Uniform Rational B-Splines) or classical splines are used for exporting data into software.

Fig.19 Frank Gehry. Bilbao Museum. Source: flickr.com, ID: dbaron

Fig.20 Zaha Hadid. Hvenhuis Photo: flickr.com, ID: adlapan

2.2. The NURBS surfaces.

NURBS is the standard for describing and modelling curves and surfaces in computer aided design and computer graphics. They provide a unified mathematical basis for representing both analytic shapes, such as conic sections and quadric surfaces, as well as free-form entities. Furthermore, this modelling principle can use a single internal representation for a wide range of curves and surfaces, from straight lines and flat planes to precise circles and spheres as well as sculptured surfaces.

NURBS is used to model automobile bodies, ship hulls, animated characters, sculptures and films. The main application for NURBS-based software has been predominantly for machinery engineering. However, after a while, with the development and popularity of architectural complexity, NURBS was applied to the building envelope. Any surface composed of NURBS is the combination of curves generated by using the verticals of a control polygon and dependent on some interpolation or approximation.

In interpolation the curve passes through the given points and assumes the given derivatives at the prescribed points so the surface satisfies the given data precisely. In approximation curves and surfaces do not necessarily satisfy the given data precisely, but only approximately. In some cases a large number of points can be generated and they contain measurement or computational noise. In this way it is important for the curve or surface to capture the shape of the data and not to go through every point generating jagged line. [9]

Approximation – curve is influenced by control points.

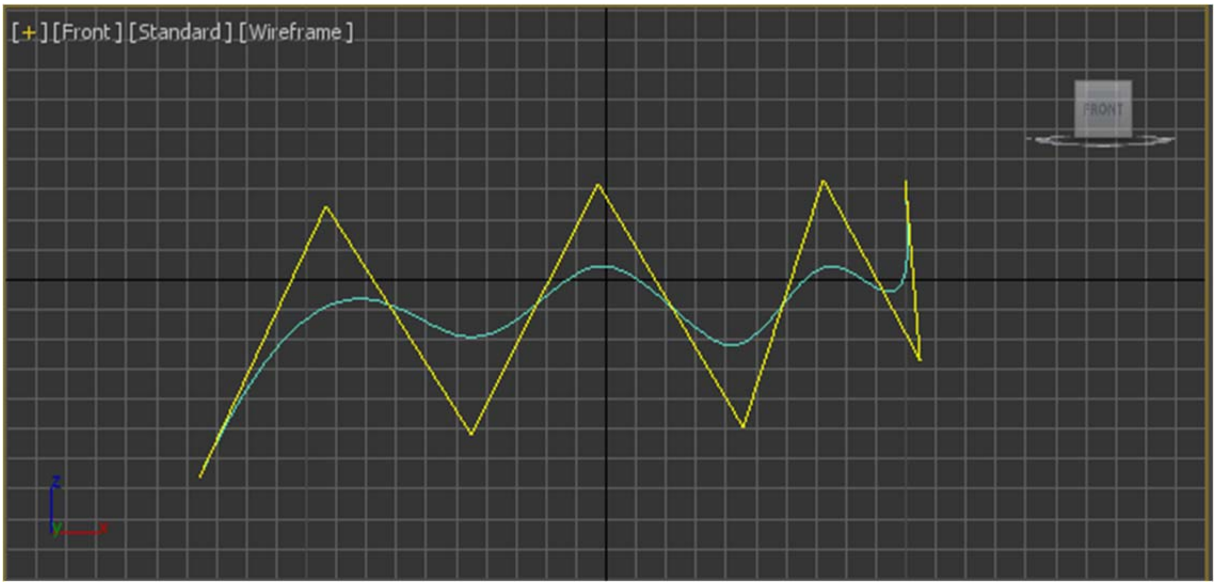


Fig.21 Approximation. Source: Author

Interpolation – curve must pass through control points.

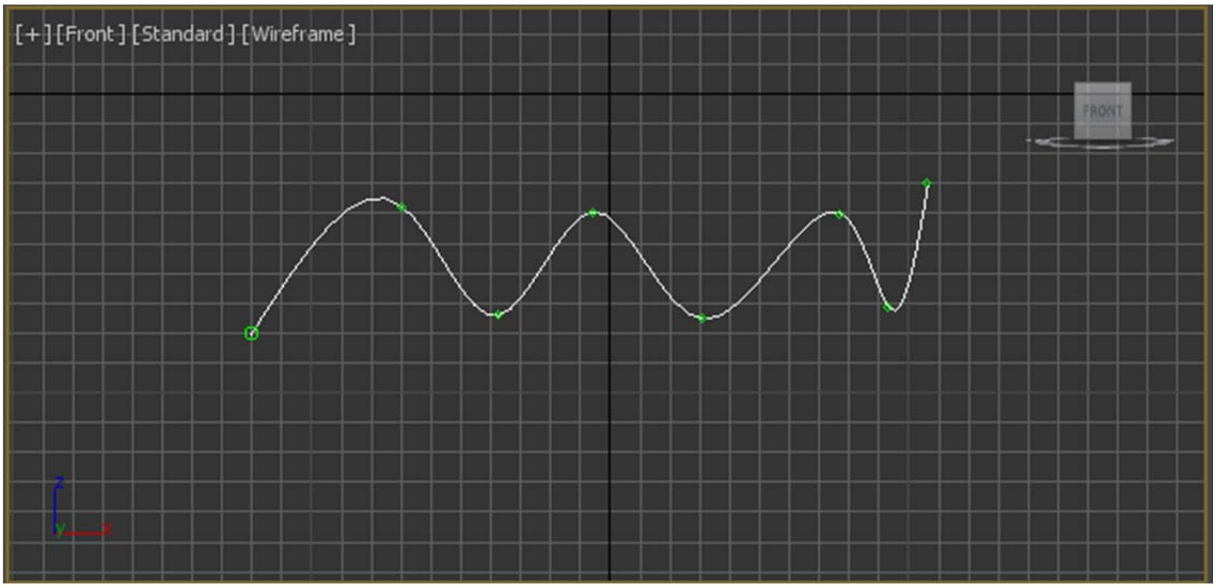


Fig.22 Interpolation. Source: Author

2.3. Binder jetting technology

The principle of binder jetting is an AM process in which a liquid binding agent (glue) is selectively deposited to join powder particles. Layers of material are bonded to form an object. Binder jetting is capable of printing a variety of materials including metals, sands and ceramics. Some materials, like sand, require no additional processing. [ExOne.com] In manufacturing, this technology is generally used to produce sand casting moulds which are regularly printed with sand or silica. After printing, the moulds are ready for casting. The casted metal component is usually removed from them after casting by breaking the mould.

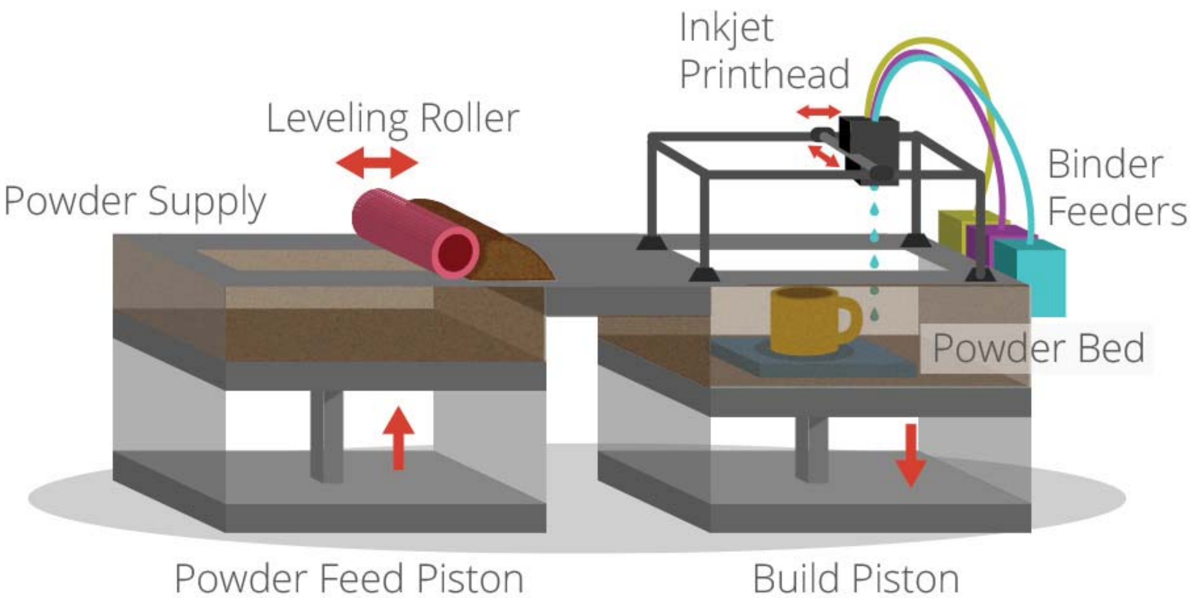


Fig.23 Principle of binder jetting Source: www.threeding.com

The Binder jetting 3D printing technology was applied to produce full-scale precast concrete slab in DFAB house in Switzerland. The principle of producing the formwork for this slab differs little from producing moulds for details in machinery. The 78m2 “Smart Slab” comprises eleven 7.1-meter-long prestressed concrete segments that were prefabricated and then joined using post-tensioning cables. Its structural system consists of a series of hierarchical curved ribs containing the post-tensioning cables, spanning around seven meters from one end to the other, reducing in height from 600 to 300 mm. Six secondary ribs are spanning the 11.7 meter length of the slab with a shallower depth of 300 mm. The prestressing tendon in the secondary ribs also mechanically connects the eleven segments once under tension. The 20 mm thick concrete fields between ribs are domed to maximize stability and to minimize the amount of material needed. [8]

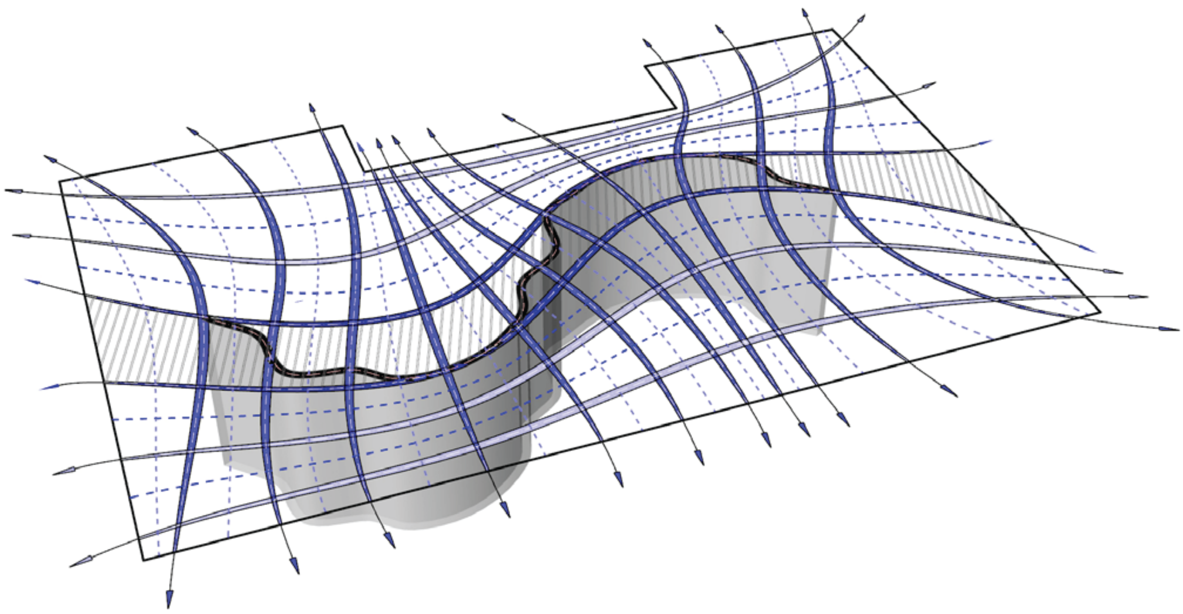


Fig.24 Post tensioning scheme of “Smart Slab”.Source: [8]

The fabrication of the hybrid formwork involved application of 3D printing and CNC laser cutting. The lower part of the formwork segment consists of assembled and sealed 3D printed parts. The upper part was cast in pre-assembled timber formwork modules, integrating the building services voids and reinforcement bars. The upstand ribs were cast inside the plywood formwork.

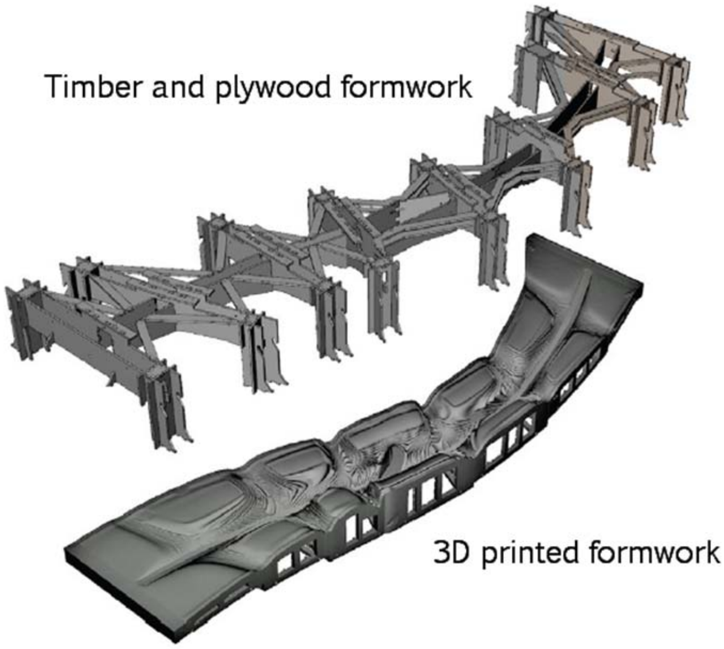


Fig.25 Assembled formwork: upper and lower parts.Source: [8]

After assembly of the 3D printed sand-formwork, the sand surface was coated with polyester resin to harden it and to allow for the application of the release agent before pouring concrete.

Fig.26 Application of the release agent.
Source: [8]

Fig.27 3D printed parts coated with polyester resin.

Source: [8]

Laser-cut plywood panels were used to fabricate the formwork for the upstand concrete ribs. These panels were pre-assembled and installed on the top of the 3D-printed formwork right after the first layer of concrete was applied.

The design of the slab reduced concrete use by about 70% compared to a conventional slab. The main reasons are the combination of a post-tensioning system, lightweight fibre-reinforced concrete and the specific geometry. Nevertheless, it is still cheaper to use more material than to design and produce an optimized slab with complex formwork. However, due to architectural demands to broaden the possibilities of producing complex concrete structures and reducing the usage of material this precast method has the potential to be developed and to expand its field of application. [8]

Fig.28 Assembled slab. Photo: [8]

2.4. CNC milled EPS formwork.

These days, sophisticated software applications in conjunction with industrial robots help to extend the design potential of complex shapes of reinforced concrete constructions. The use of easily workable materials like polystyrene for the fabrication of formwork enables productivity enchantments, cutting costs and also recycling the used material after production.

The current trends in architecture call for extensive progress in the area of the processing technology and execution of reinforced concrete members. The ambitions of the most prestigious modern architects whose projects have gone into the history books in world architecture, requires the use of irregular shaped moulds that do not seem feasible at first sight. One of such artists is Frank Gehry, known in the Czech Republic thanks to the ”Dancing House” built in Jirásek Square in Prague in 1996.

Fig.29 The Dancing house. Source: dancinghousehotel.com

Mr. Gehry's buildings reflect the spirit of experimentation, obsession with motion, dynamics and uniqueness. One of the main styles of the architect's creations is deconstructivism – a style characterized by irregularity in shapes and denial of accepted architectural standards. Each building in this style requires a series of designs and complicated solutions in the construction process and maintenance.

Fig.30 "Der Neue Zollhoff". Source: flikr.com, ID: Demis de Haan

The complex composed of three buildings A-B-C and called "Der Neue Zollhoff" [New Customs-Yard] was erected on the east bank of the Rhein River in Düsseldorf on the site of the existing customs-yard near the North Rhein-Westphalia state administration complex.

All the three buildings are designed with a skeleton slab system using different materials on the façades. Building A has a façade of white plaster, while the façade of Building C is of red brick masonry and the middle Building B has a shiny stainless steel façade reflecting the colours of the neighbouring buildings. Façade B is attached to a monolithic precast wall of a complex shape, the "Curtain". The complex of the buildings was constructed by the Philipp Holzman AG Company in 1994-1999. The formwork of CNC-machined expanded polystyrene was used in the construction of precast monolithic walls of complex shapes. The manufacturing principle consists in cutting out a mould from a unit 2.4x3.4x0.9m (WxHxT) in dimensions with a CNC machine, embedding reinforcement and pouring concrete in it. Concrete is then manually smoothened and spread. All the moulds were recycled after use together with fine polystyrene particles arising during the process. A total of 355 precast panels were manufactured, each with its own individual shape. The completed precast units of Building B do not have a load-bearing function, but form the building envelope on which the shiny steel façade was assembled.

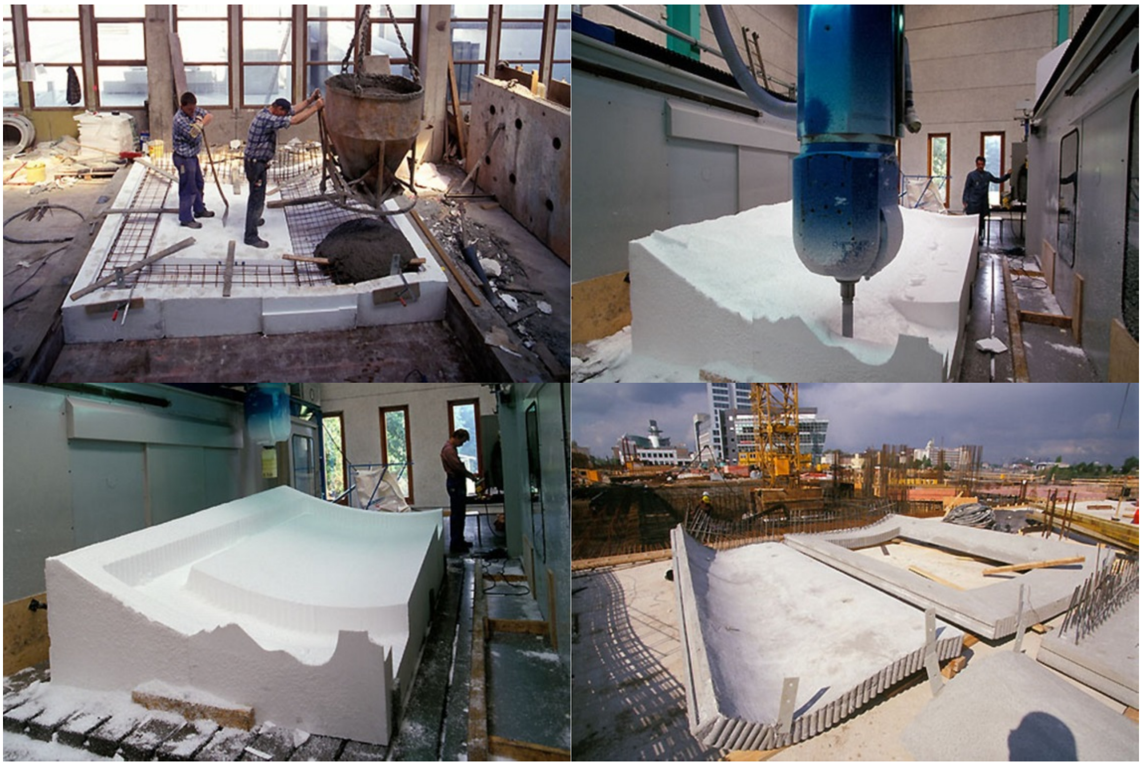


Fig.31 Fabrication of panels. Source: [25]

High precision in the manufacturing of reinforced concrete precast units was achieved thanks to the CAM (Computer Aided Manufacturing) principle, which had not been so widespread worldwide in the 1990s. In the design, the Gehry Partners architectural firm used the CATIA (Computer-Aided Three-Dimensional Interactive Application) software by the Dassault Systems SE Company. The designed model served as a "single source of information" and a component part of the contract and implementation documentation. This coordination method provided the architect with an option of sharing precise information with the contractors and manufacturers, who could then use it for price calculations and pass technical parameters to manufacturing plants. The principles used in 1994 as Know-How have currently become indispensable for large construction projects nowadays. [1]

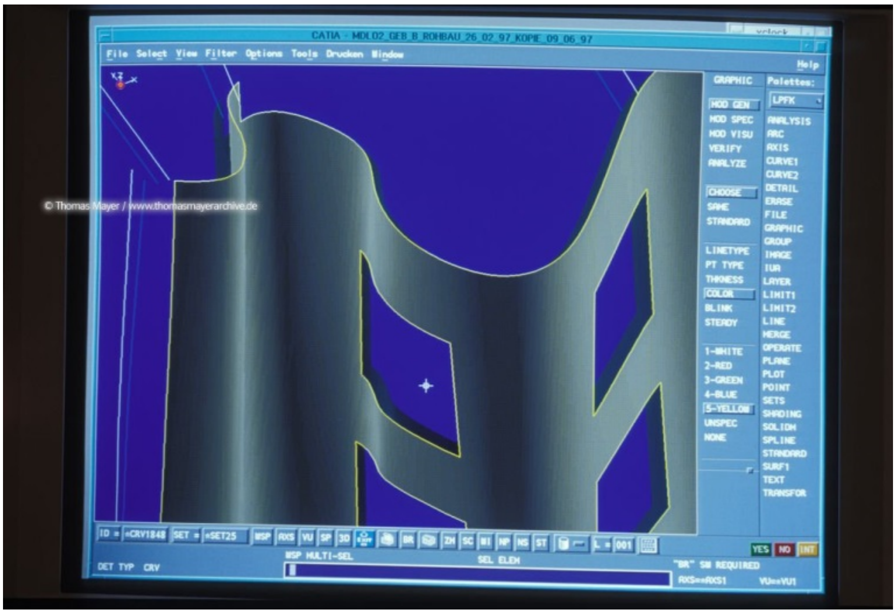


Fig.32 Facade model in CATIA software. Source: [25]

The ”Spencer Dock Bridge“ over the Royal Canal, situated in Dublin, with a span of 40m and 25m in width, accommodates car, tramway and pedestrian traffic. The bridge was designed by the Amanda Levete Architects studio and built by the Laing O'Rourke Company in 2009. The lower bridge part connects the canal banks in a single smooth plane with grooves in concrete specially designed for highlighting the shape irregularities. The concrete surface is reflected from the dark canal waters and is lightly illuminated at night from the bottom. In the middle of the bridge, the pavement edges are widened forming the so-called viewing zone with a view of the docks, St. Lawrence O'Tool Church and the Linear Park. The structural part of the bridge was made of monolithic in-situ reinforced concrete and, successively, a pre-stressing system was installed in the upper part. A total of over 100 pieces of formwork of CNC-machined EPS blocks was used during construction. The CAM principle allowed reaching the required precision rates. The formwork for the bridge in Dublin was manufactured with a 5-axis CNC machine. After CNC-machining, the EPS block surface was coated with several layers of Polyurea and the sprayed-on material was smoothened with abrasive paper. Prior to formwork assembly, the canal was dried and a support bearing construction was built under the EPS blocks. During the in-situ assembly, the joints of individual EPS blocks were filled with PUR foam and smoothened to achieve a perfect surface.[29]

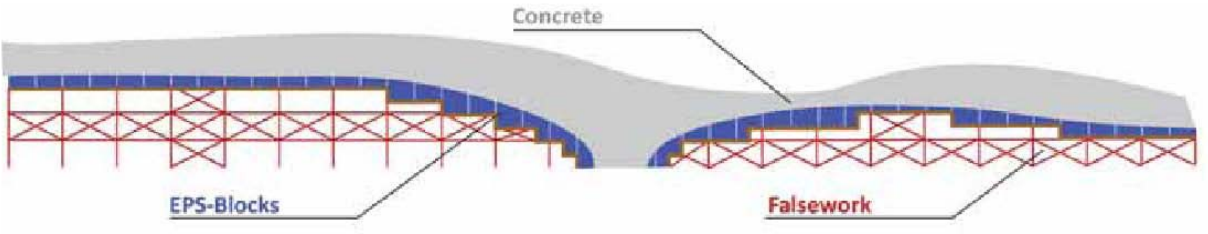
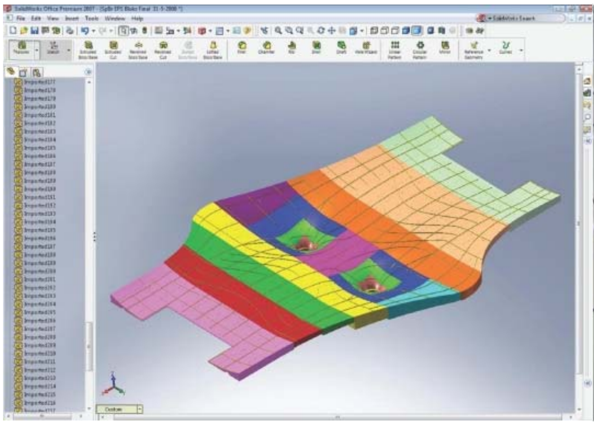


Fig.33 Falsework and formwork scheme. Source: [17]



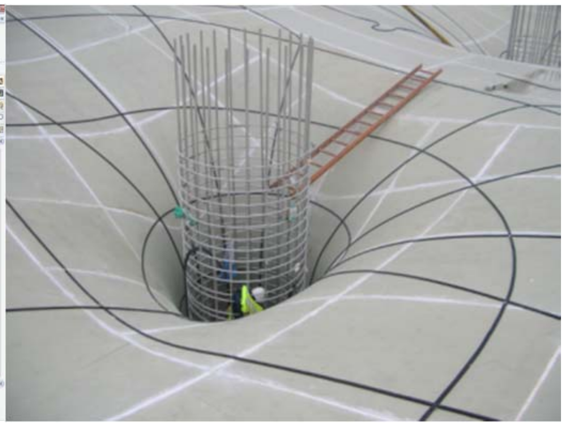


Fig.34 Formwork model in SolidWorks software *Fig.35 Assembled formwork*

Source: Nadcam.com

2.5. The EPS properties and processing techniques

Polystyrene formwork blocks have excellent properties in terms of practicality, economy and effectiveness. The use of EPS blocks helps to save time and costs, and, unlike steel and plywood alternatives, they are easy to handle and workable. As for the ecological aspects, polystyrene is a well recyclable material. Several types of tools can be used in the machining and shaping of EPS blocks. The most widespread tool is the CNC machine, which has hardly any shape limitations, but its disadvantages are the necessity of replacing the drill bit frequently during machining due to permanent friction and large amounts of polystyrene dust arising during cutting. Unlike the CNC machine, a great advantage of the hot wire cutter, which cuts polystyrene blocks into desired shapes, is that no dust arises during cutting and the cutter is resistant to overheating. The employment of an industrial robot in cutting EPS blocks allows reaching high precision rates in production. This technology has been used several times worldwide. One of the most important aspects of employing polystyrene formwork is the block surface treatment before pouring concrete. It is a well-known fact that expanded polystyrene foam has a closed-cell structure with voids formed during expansion in its production, which can have an undesirable effect on the concrete surface quality. The type of cut polystyrene can also affect the production of concrete members. There are currently various EPS types available for application even outside the building industry. The principal difference is the polystyrene density ranging within 15kg/m^3 – 40kg/m^3 and the fineness of expanded particles.

Tab.2 Polystyrene densities. Source: twinplast.be

Type	*Density*
EPS 60	15kg/m^3
EPS 150	25kg/m^3
EPS 200	30kg/m^3
EPS 250	35kg/m^3
EPS 300	40kg/m^3

After cutting out a block, the polystyrene surface must be treated to create a smooth, strong and resistant surface to distribute and carry the load of liquid concrete and reinforcement and to apply formwork release agents. There are five types of polystyrene treatment performed for different purposes of formwork members:

- **Polyvinyl chloride (PVC) film**

The PCV film allows easier application without additional surface treatment. It is easily applicable and forms a fine orange peel texture on the concrete surface. The disadvantage is that the film has limitations in applying on double curved surfaces.

- **Polystyrene foil**

Unlike PVC films, polystyrene foils are available in thicknesses of 1mm and 2mm, which makes them by several times thicker and, therefore, they create a smooth and even surface. The disadvantage is that the 2mm foil can only be used on planar surfaces and the 1mm foil only on single curved surfaces.

- **Epoxy resin**

Epoxy resin can be used on surfaces of different shapes. The easily applicable substance serving primarily for consolidating polystyrene surfaces is widely used in the cinematograph and modelling. The disadvantage is the workability time, which requires a perfect mould treatment with a brush to prevent the run.

- **Polyurea**

The sprayed-on waterproofing coating is applied not only as a waterproofing membrane of roofs and swimming pools, but also in the treatment of EPS formwork blocks. Polyurea is applied in several layers and after hardening it can be smoothened to create a perfect and even surface of architectural concrete.

- **Wax**

Wax can be easily applied onto the surface of a complex shape. It is easily workable and greasy, which is of importance during the formwork removal from concrete members.

3. Applying of Robotic Hot Wire Cutter technique in the formwork fabrication

The modern architecture demands for expanding opportunities in producing non-standard and complex constructions. It is seemed to be a tendency to design projects with unconventional and groundbreaking shapes. Nowadays, the topic of applying industrial robots in producing the formwork is not widespread. However, there are several examples of high-tech performance in Europe, which had confirmed the precision and feasibility of this method. The purpose of this experiment was to produce the complex formwork for concrete wall with applying of expanded polystyrene (EPS) blocks, hot wire cutter and industrial robot "KUKA KR 10 R1100". RHWC is a process where robotically controlled and electrically heated wire cuts polystyrene foams, replicating the geometry by a 3D or CAD model. This method enables to produce complex geometry formwork for concrete casting. Used formwork and cut-offs can be recycled for new insulation or formwork products.

Aims of the experiment:

- Apply RHWC method on a small scale structure
- Select a strengthening coating for EPS and apply it to a concrete contact area
- Convert the CAD models into a code
- Design a plywood falsework for reinforcing the EPS formwork

3.1. Equipment and materials

1. Industrial Robot "KUKA KR 10 R1100". – Compact robot with floor, ceiling and wall mounting options.

Technical data:

Maximum reach – 1101 mm

Maximum payload – 10 kg

Number of axes – 6

Weight – approx. 55 kg

Fig.36 Industrial robot KUKA "Agilus"
Source: kuka.com

2. Hot wire foam cutter "Schiwa Junior 100"- professional device designed for precise, fast and waste-free cutting of EPS insulation boards. The hot wire cutter enables any machining of polystyrene blocks in all possible variants: straight cut, angular cut, rabbet, wedges.

Technical data:

Cutting height: 400 mm

Cutting width: 1000 mm

Transformer: 24 V – 240 Watt – 3 A

Fig.37 Hot wire foam cutter "Schiwa Junior 100"
Source: shop.schiwa-styroporschneider.de

3. Expanded polystyrene block "Styro EPS 100F"

Size 1000x300x600 mm

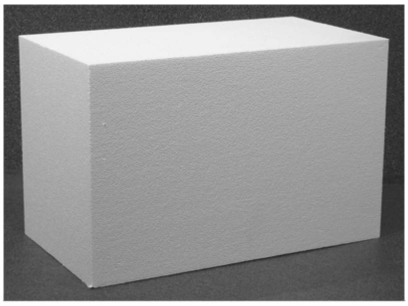


Fig.38 EPS block.
Source: hotwirefoamfactory.com

4. Epoxy coating "Smooth on" Epsilon PRO

The thixotropic epoxy coating for hardening styrofoam surface.

Fig.39 "Epsilon PRO". Source: smooth-on.com

5. 14 mm-thick plywood formwork.

Plywood was used for falsework manufacturing.

Fig.40 Plywood. Source: peri.com

3.2. Applied software

1. Rhino 6 – 3D computer graphics and CAD application software developed by Robert McNeel & Associates.
2. AutoCAD - commercial drafting and CAD software application developed by Autodesk.
3. Notepad ++ - source code editor and text editor.
4. WorkVisual 4.0 for KUKA System Software – software package for KR C4 controlled robotic cells

3.3. Wall design

For each used surface, two boundary control curves must be modelled, see Fig. 41. The size of the material member and the tools for machining the members should be adjusted to these curves. In the study, Styro EPS 100F expanded polystyrene with dimensions of 1 m x 0.5 m x 0.3 m was machined. The length of the hot wire (Schiwa Junior) is 100 cm. If the resulting construction is bigger than the maximum size of EPS block, the overall shape and figure are mapped and a greater number of formwork units are successively fabricated. The units will be numbered for their resulting assembly into a larger surface.

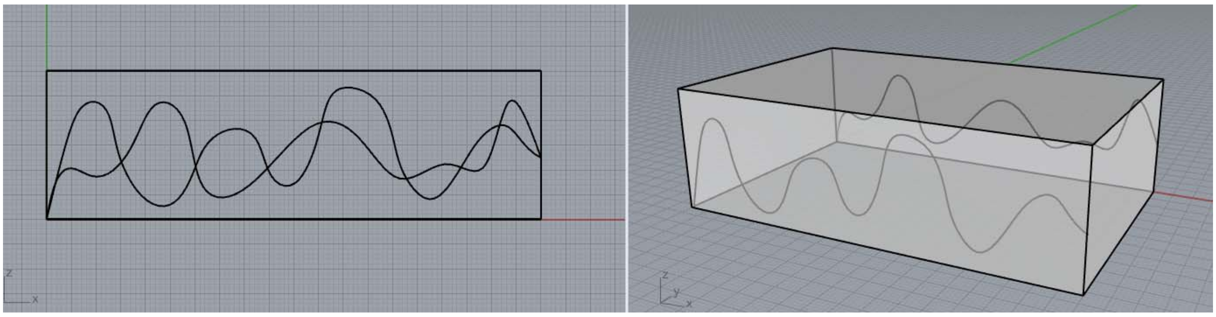


Fig.41 Modelling boundary curves of a cut. Source: author.

Fig. 42 displays the scheme of the modelling process and fabrication of formwork for complex architectural shapes.

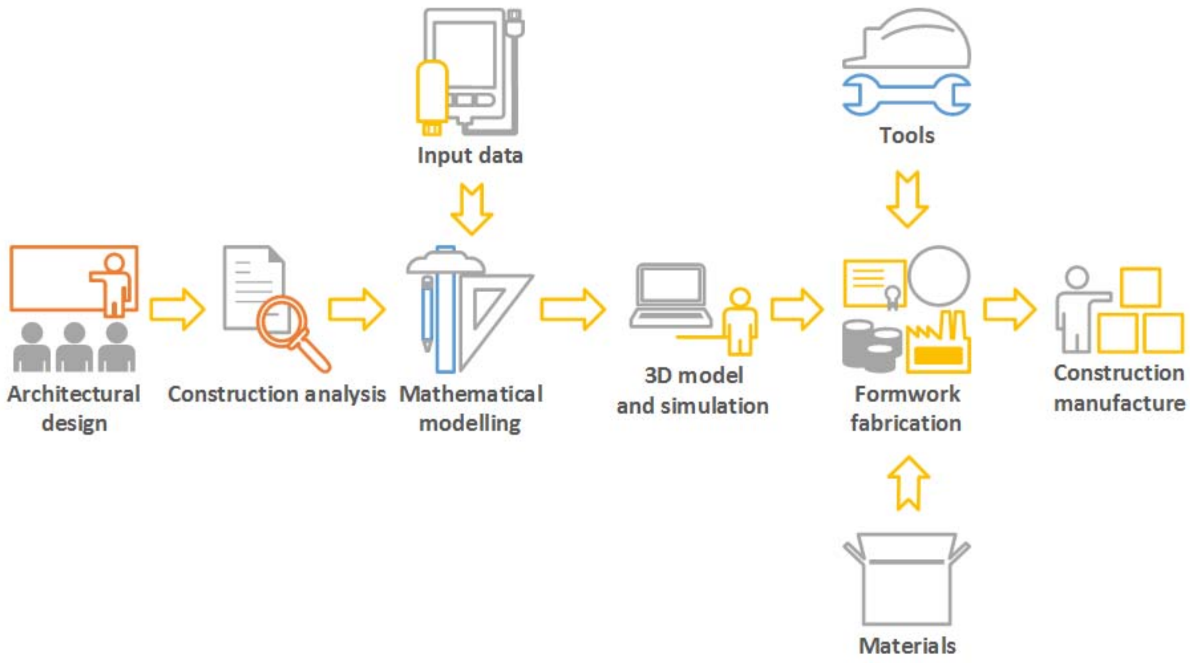


Fig.42 Working procedure of formwork fabrication. Source: author.

In choosing the shape of boundary curves of a structure, the architect can select from two modelling methods: analytic and manual modelling.

The above two design procedures of the resulting formwork surface principally differ in the approach to the modelled object. In the case of analytic design, the architect roughly selects the shape of the curves to successively implement the mathematical apparatus, describe the function of the curves, define smooth transitions and boundary points. Then, based on the analytically described boundary functions, a surface can be parametrically described for each interval. For each point of the analytically described surface area of the resulting construction, the normal vector can be defined which will serve as the directional setting of the robotic hand end tool for further machine surfacing such as grinding, applying a thermal insulation layer, plastering, painting, etc. It is advisable to use the following algorithm for a smooth connection of different curves and parametric modelling of the surface area.

3.4. Modelling and fabrication of formwork for complex concrete members

Manual modelling of curves in 3D simulation SW. Fig. 43 displays a flowchart describing the successive steps in the design of polystyrene formwork for complex architectural shapes using the RHWC technology from the manual modelling process to the formwork fabrication.

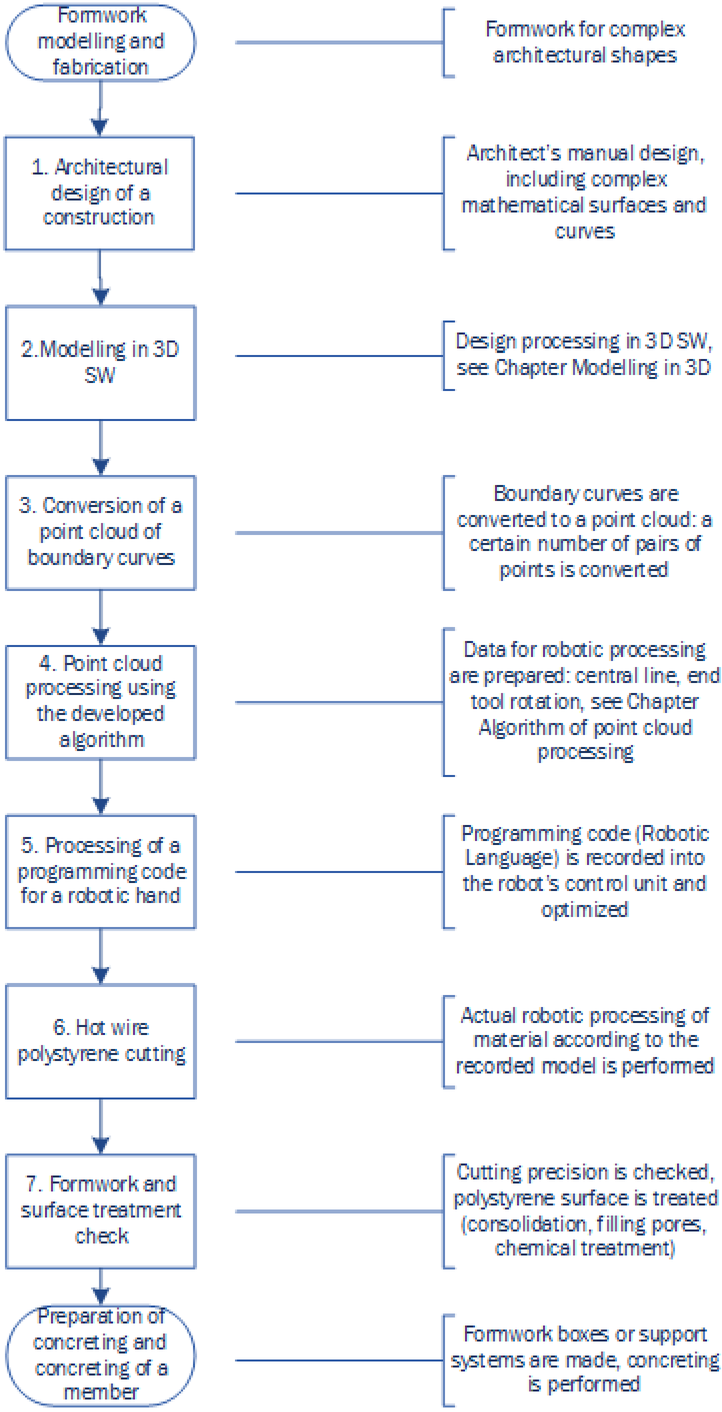


Fig.43 Flowchart of formwork fabrication for complex architectural shapes. Source: author

3.5. Modelling of curves in 3D software

The Rhino 6 SW was selected for the modelling of a practical functional specimen. The modelling of curves in 3D SW includes the following successive steps:

- Step 1: Manual design digitization – drawing of boundary curves: the scale or the coordinate system need not be preserved for the sake of simplicity, it suffices to respect the proportional 3D properties of an object. The algorithm converts and adjusts the material size input data, see Fig. 44.

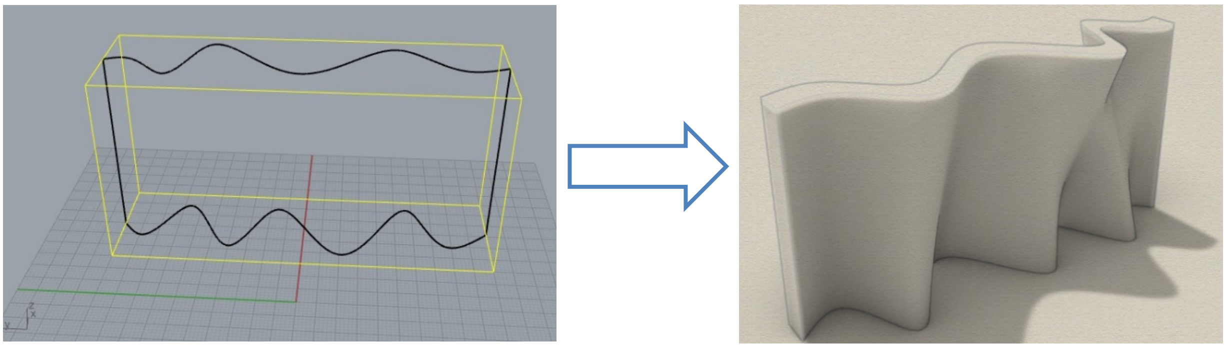


Fig.44 Digitalization of architect's manual design. Source: author

- Step 2: Creation of a continuous surface between boundary curves: the surface is created by the translation of a line (imitation of hot wire cutting) along two trajectories: the upper and lower curve. To create a fine polygon mesh of the surface at least 100 central intermediate curves are selected, see Fig. 45

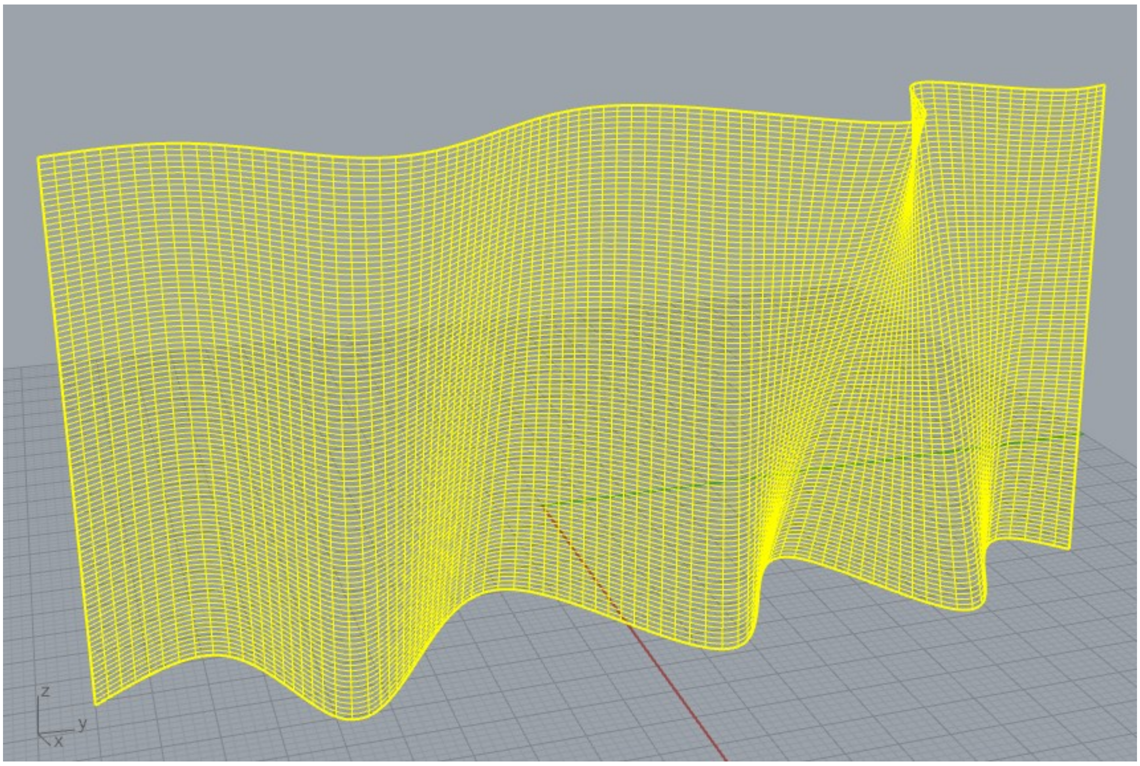


Fig.45 Creation of a continuous surface of an object. Source: author

- Step 3: Creation of a 3D member using an instrument – extending a continuous surface to the required thickness of a 3D object, see Fig. 46

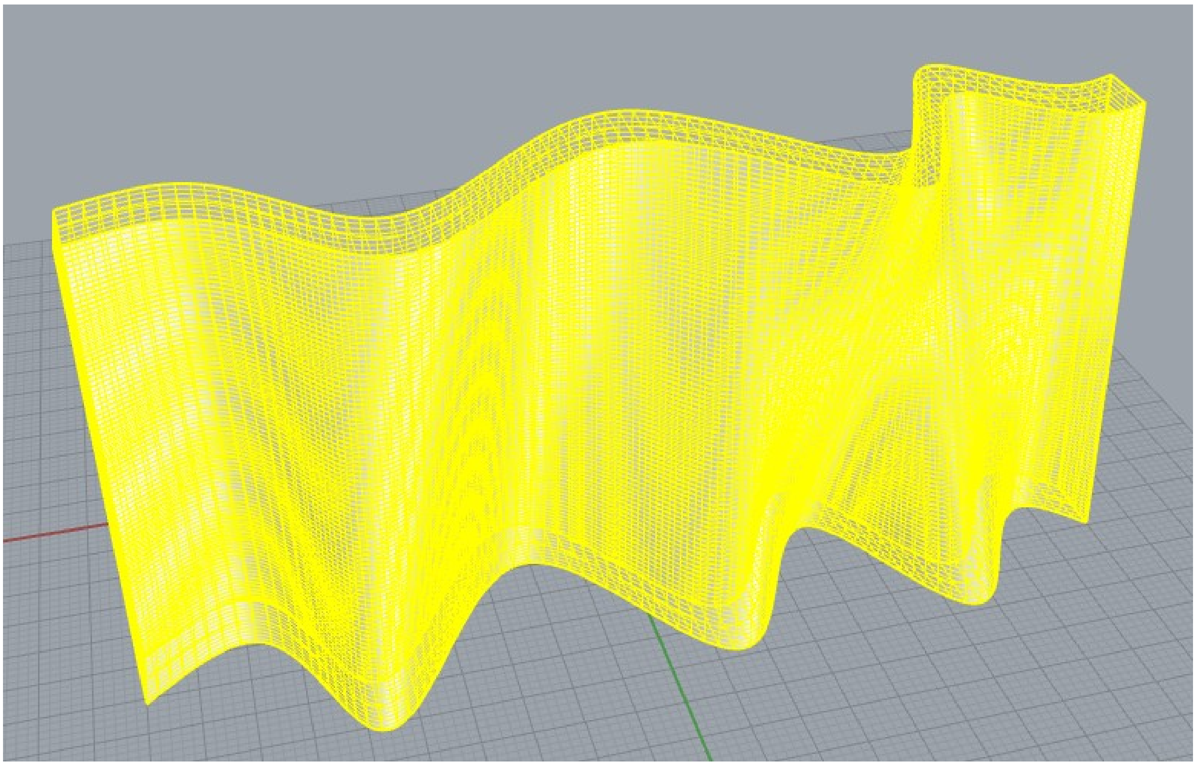


Fig.46 Creation of an enclosed continuous 3D object. Source: author

- Step 4: Rendering a 3D object according to the required appearance. To enhance the model the correct texture size and lighting, including shadows, are defined, see Fig. 47

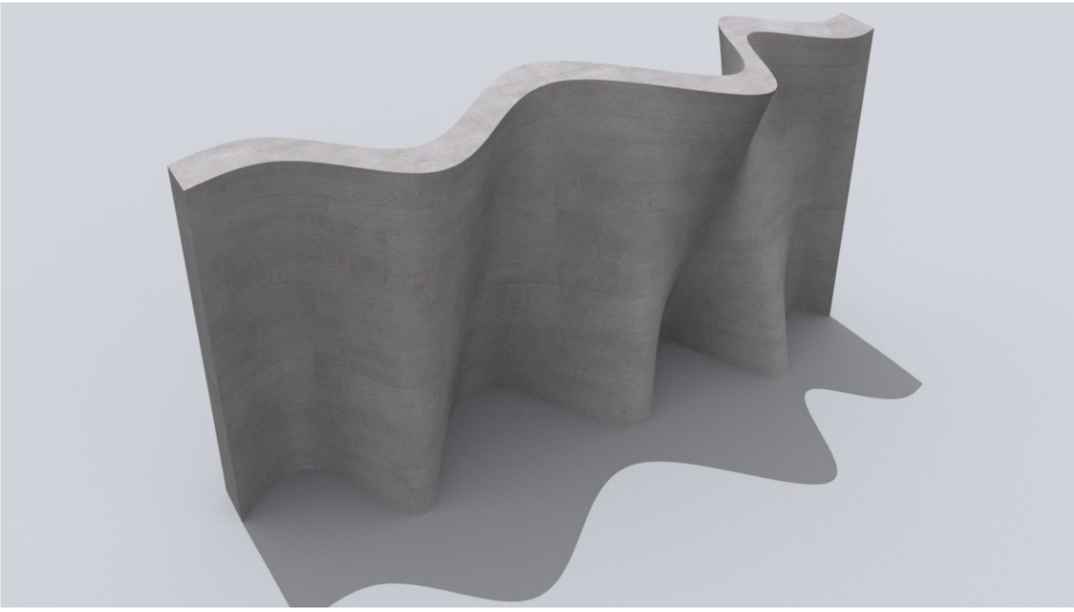


Fig.47 Resulting rendered 3D object. Source: author

- <u>Step 5</u>: Analysis of the structure. In this step, we define the basic parameters of the structure: curvature analysis, wall area, member volume, mass, position of the centre of gravity, moments of inertia and lengths of edges. see Fig. 48.

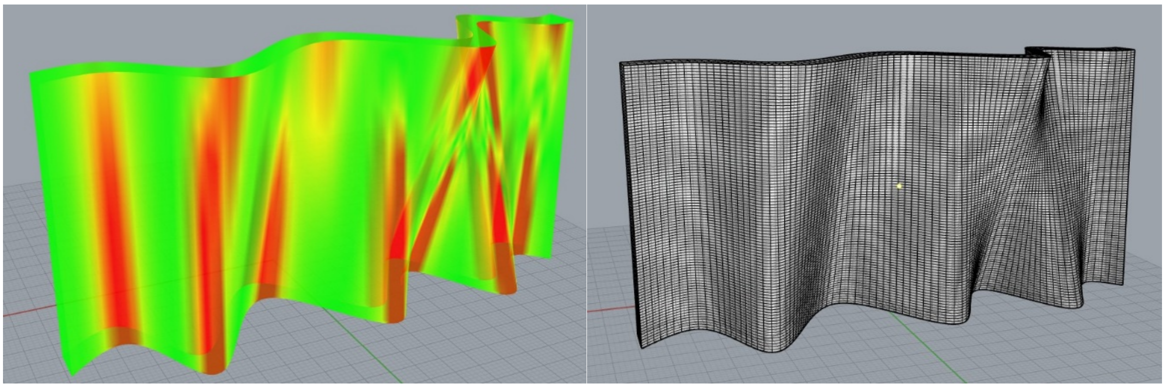


Fig.48 Analysis of the resulting model of a 3D object. Source: author

Additional parameters were identified for the test specimen of a 3D wall, see Tab. 3. These parameters were successively compared with the actually manufactured specimen. The measured deviations are described in the Tab. 3.

Tab.3 Basic model parameters and comparison with reality. Source: author

Parameter	*Model*	*Reality*	*Unit*
Volume of object	0.039	0.041	m^3
Mass of object	97.5	102.5	Kg
Object face area	0.647	0.671	m^2
Upper curve length	129.8	131.2	Cm
Lower curve length	160.6	162.4	Cm

3.6. Point cloud processing

The smooth movement of a robotic tool required providing the necessary number of points lying in local extremes and in places where the condition of a smooth connection of curves applies. For a robotic hand, the central line of the end tool motion and the spatial angular rotation of the tool or the motion trajectory consisting of smoothly connected points is essential. For each robot's position is described by 6 variables: 3 coordinates in space [X, Y, Z] and 3 angles of rotation [A, B, C].

It is important to set the limits straight away and define how the reference points on both curves will be selected. The condition of motion along the central line implies the identical number of reference points on each curve where each pair of points unambiguously describes a point on the central line. There are three ways of selecting points on boundary curves:

- random
  Advantages: simple calculation
  Disadvantages: non-uniformity of the speed of motion of both ends of the robotic tool, greater tool rotation in space
- uniform according to the length of curves
  Advantages: uniform speed of the tool motion, smaller angles of tool rotation in space
  Disadvantages: more difficult calculation, higher load acting on robotic hinges, more difficult motion smoothness
- uniform according to the projection plane or according to vertical cutting surfaces
  Advantages: uniform speed of the tool motion, lower load acting on robotic hinges, motion smoothness
  Disadvantages: modelling surface does not fully correspond to the real one, non-uniformity of the speed of motion of both ends of the robotic tool

Having tested all the above methods of point selection, it was decided to use the uniform conversion of points according to the length of curves, which is the optimum choice for the cutting tool. The total length of each of the curves was divided into the same number of intervals, and a pair of points from the Rhino 6 SW was converted e.g. via the *.EPS vector format as the input data for the conversion algorithm. After being processed, the output data was used to create the KRL (KUKA Robotic Language) code in WorkVisual software.

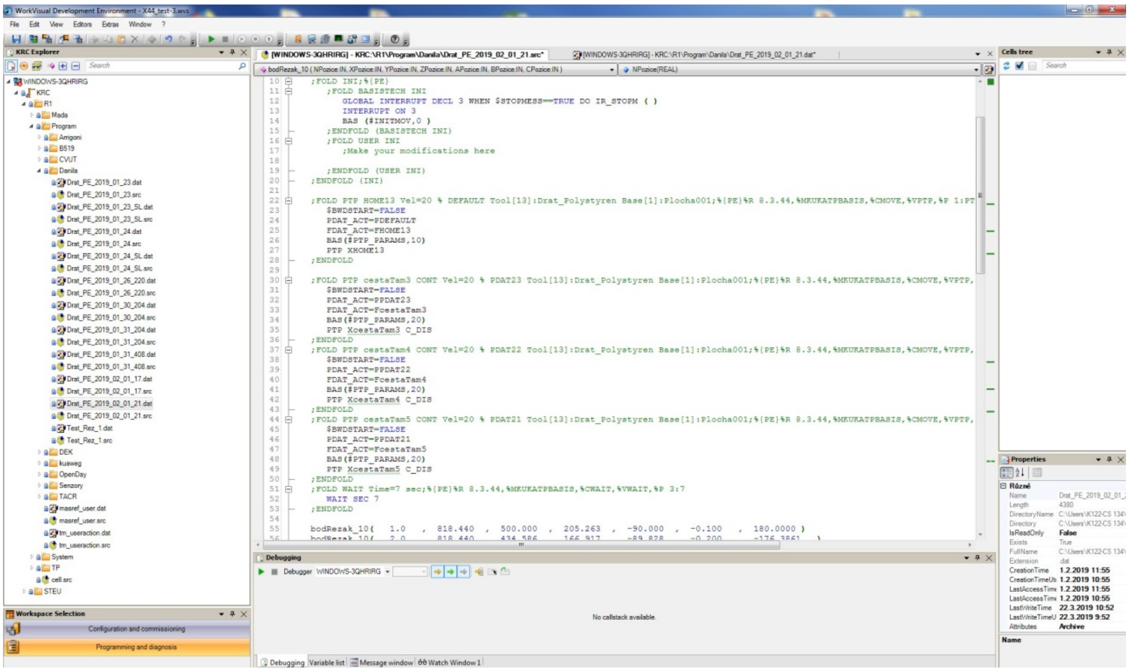


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Fig.49 WorkVisual DE – KRL code. Source: author*

*Find full KRL code in attachment

3.7. Practical example of formwork fabrication using RHWC technique

The experiment took place in “Experimental Centre” (“EC”) laboratory of the Czech Technical University in Prague with the assistance of “EC” workers, who supplied an author with all necessary equipment and materials. All operations was precisely controlled and supervised by Ing. Vyacheslav Usmanov Ph.D.. The experiment was composed of next stages: architectural sketch, modelling and rendering, development of algorithm for exporting data, data export and processing, hot-wire tool assembly, formwork fabrication, falsework fabrication, formwork coating and concrete pour.

Fig.50 KUKA robot with hot-wire tool. Source: author

The initial station was prepared, the initial point of cutting measured, the height for material set up and the material surface were levelled. The work bench seating surface was secured against material slippage. For each density and material structure, a corresponding speed of the hot wire trajectory must be chosen according to the wire temperature. The wire temperature can be regulated by the input voltage. The wire cannot be stretched like a string, nor can it stay in one position burning the material in one place for an unnecessarily long time.

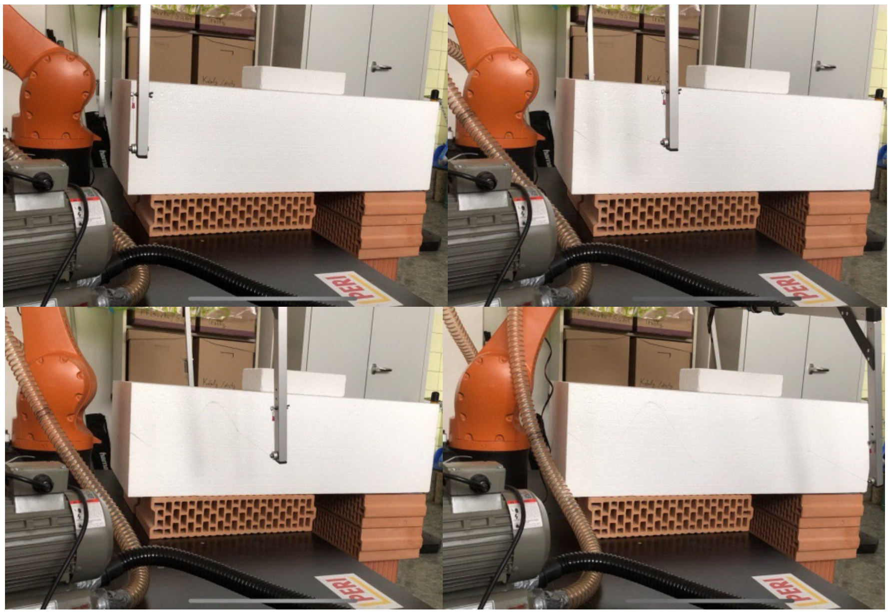

Fig.51 Cutting the EPS block. Source: author

Material cutting was started. Ventilation and forced air using filtration must be provided to exhaust products of combustion to comply with health and safety regulations. Protective eye goggles and a respirator with a protection factor against products of combustion and smoke are recommended for personal protection.

Fig.52 The EPS formwork. Source: author

After cutting, the fabricated member must be checked for: geometry, surface quality, porosity, material defects. The check includes deviations from straight cutting, wall evenness and corner angles. In the case of detecting greater irreparable defects, one more formwork specimen must be fabricated.

The polystyrene surface that comes into contact with a building material is treated with epoxy coating. The working surface must be consolidated, waterproof and inactive to acetone-based chemical substances. The voids of open pores should also be filled with a substance. Special surfacing is applied to add the polystyrene surface a smooth and shiny look. Paints for correcting bumps and various falls across the cross section must be applied in several layers.

Fig.53 Coating the EPS formwork surface. Source: author

The formwork member is dried and its surface is successively checked for defects and one more protective coating layer is potentially applied.

The falsework was made of waterproof plywood. The falsework box should allow the rectification for a smooth change in the member thickness. Polystyrene should be appropriately secured against slippage, movement and potential washout. The falsework box joints should be tight.

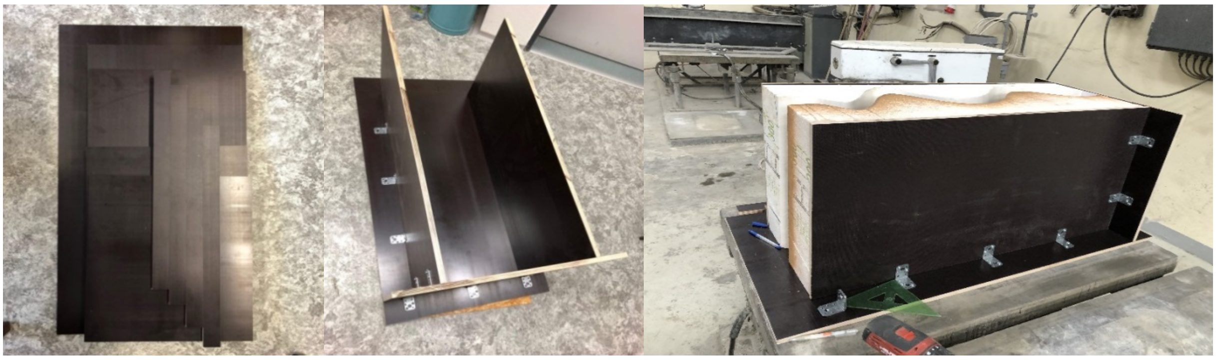

Fig.54 The falsework assembly. Source: author

Fig.55 Finishing touches. Source: author

Final treatment before concreting is performed: a logo is attached; formwork release oil applied on the mould and the falsework box, the box is closed, placed onto a vibration bench.

The members are concreted with a mixture whose composition is not the subject of this article. The mixture composition must be carefully selected in advance with respect to the size and shape dimension of the resulting construction. For some structures, plain concrete is not suitable and high-strength concrete or special concrete with recycled materials is recommended for use. The resulting structure is covered with plastic foil to prevent shrinkage cracking.

Fig.56 Pouring. Source: author

The formwork was removed according to the technologist's recommendations, after 24 to 48 hours. The formwork removal time depends on the type of mixture and, e.g. for a special mixture of fly ash concrete, it is around 24 hours. After the box dismantling, the formwork is carefully separated from the concrete member. Damaged pieces of polystyrene formwork were recycled.

Fig.57 Removing the formwork. Source: author

The completed member is checked for visual surface defects, cracks, surface air bubbles, colour shade, edge and wall integrity. In the end, the logo is highlighted, the pedestal mounted, etc.

Fig.58 Rendered 3D model.
Source: author

Fig.59 Fabricated concrete member.
Source: author

The model is compared with the completed member checking the actually measured values against the model outputs.

3.8. Full scale application of the double-curved wall

Fig.60 Revit model of reception. Source: author

A full scale prototype was designed as the supporting wall of the roof of the reception. A double-curved wall has not only a load bearing purpose but an aesthetic one. The wall should be installed with proper illumination and finishing.

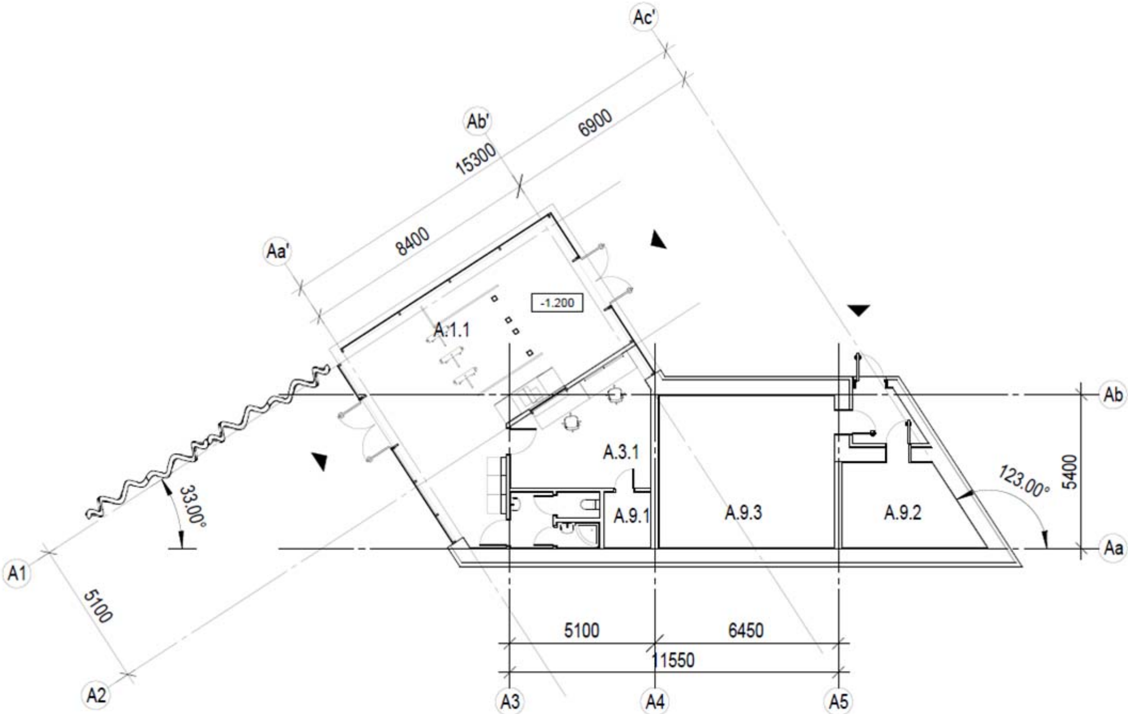

Fig.61 CAD ground plan of reception. Source: author

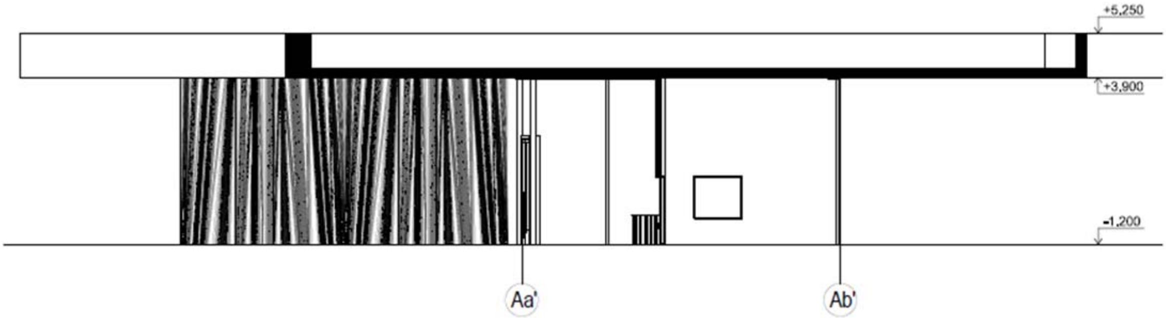

Fig.62 CAD front view. Source: author

4. Multi-Criteria Decision Analysis in selection of optimal formwork fabrication technique

For choosing the optimal formwork manufacturing technique the Multi-Criteria Decision Analysis (MCDA) method was applied to three alternatives. The MDCA method is integrative evaluation method in the sense that it combines information about the performance of the alternatives with respect to the criteria (scoring) with subjective judgements about the relative importance of the evaluation criteria in the particular decision making context (weighting).

The analysis was provided with next criteria: cost [CZK/m^3], manufacturing velocity [min/m^3], production waste level [1-10], ability to produce the double-curved surfaces [Y-N], ability to produce freeform surfaces [Y-N], coating cost [CZK/m^2], fire risk level [1-10]. Each criterion was weighed, due to its importance, and rated due to its performance score. In the author's opinion the most important performances of the formwork manufacturing are:

1) Cost [CZK/m^3] – weighed 0.29

2) Manufacturing velocity [min/m^3] – weighed 0.23

3) Ability to produce freeform surfaces [Y-N] – weighed 0.17

Each performance was rated with a numerical score:

1 – Low. 2 – Middle. 3 – High.

The data of the RHWC technique was discovered and precisely calculated during manufacturing of the double curved concrete member. The performances of Robotic milling and Binder jetting techniques were taken from the "KM Robotics" company and the "Liaz Pattern shop" web pages.

The fire risk level was defined by the author from 1 (fire-safe method) to 10 (extremely fire-hazardous method). The RHWC technique was rated 7 because of the hot wire that is heated up to 600 degrees Celsius. During the cut the light white smoke is usually emerged, this fact confirms that laboratory should be equipped with the fire detection system and fire extinguisher. The production waste level represents the amount of waste, its complexity for cleaning purposes (dust/grains/small chunks) and environmental impact. For example the Robotic milling technique was ranked 8 because of great EPS dust amount during milling and constant necessity to change overheated drills.

Tab.4 The RHWC method data.

RHWC	Weight	Performance	Performance Score	Weighed performance
Cost [CZK/m^3]	0.29	2300	3	0.857
Manufacturing velocity [min/m^3]	0.23	12,7	3	0.686
Production waste level [1-10]	0.09	2/10	3	0.257
Double curved surfaces [Y-N]	0.03	Y	3	0.086
Freeform surfaces [Y-N]	0.17	N	0	0.000
Coating cost [CZK/m^2]	0.06	1000	2	0.114
Fire risk level [1-10]	0.14	7/10	1	0.143
summm.	1.00			**2.143**

Tab.5 The Robotic milling method data.

Robotic milling	Weight	Performance	Performance Score	Weighed performance
Cost [CZK/m^3]	0.29	4900	2	0.571
Manufacturing velocity [min/m^3]	0.23	480	1	0.229
Production waste level [1-10]	0.09	8/10	2	0.171
Double curved surfaces [Y-N]	0.03	Y	3	0.086
Freeform surfaces [Y-N]	0.17	Y	3	0.514
Coating cost [CZK/m^2]	0.06	800	3	0.171
Fire risk level [1-10]	0.14	4/10	2	0.286
summm.	1.00			**2.029**

Tab.6 The Binder jetting method data.

Binder jetting	Weight	Performance	Performance Score	Weighed performance
Cost [CZK/m^3]	0.29	6700	1	0.286
Manufacturing velocity [min/m^3]	0.23	160	2	0.457
Production waste level [1-10]	0.09	6/10	1	0.086
Double curved surfaces [Y-N]	0.03	Y	3	0.086
Freeform surfaces [Y-N]	0.17	Y	3	0.514
Coating cost [CZK/m^2]	0.06	1100	1	0.057
Fire risk level [1-10]	0.14	1/10	3	0.429
summm.	1.00			**1.914**

As the result of the analysis, it has been concluded that in comparison of three methods the RHWC technique is the optimal one. Rated 2.143 the RHWC technique has the highest manufacturing velocity and minimal cost. Nevertheless, this method has its limitation in ability to produce the formwork for freeform structures.

5. Future development perspectives and research study results

During the research study, it was managed to find the optimum algorithm for the conversion of a manual 3D design of a hyperbolic surface to an analytically described surface. The algorithm uses a series of mathematical methods subdividing gradually the surface into processable intervals to successively convert, with a minimum deviation, the curves to surfaces describable in a parametric way. The analytic description of the curves and surfaces allows a very precise surface treatment and machining using robotic technology and precise orientation of the end tool of the robotic device to the hyperbolic surface. The hyperbolic surfaces fabricated by robots serve as the formwork for the production of complex architectural shapes.

The developed algorithm, among others, enables immediate data conversion to the environment of industrial robots performing, at the same time, multi-criteria decision making for the optimum selection of the trajectory and the robotic device motion to minimize costs, material, energy, machining time and environmental impacts. An undisputed advantage of the developed procedure is further use of the mathematical model with analytically described curves and surfaces allowing trouble-free and highly precise additional surface machining like grinding, surface consolidation, reinforcement, concreting and successive surface treatment of the concrete member.

The algorithm was tested on a practical example. A concrete wall was designed and modelled in the non-uniform rational basis spline (NURBS) application, and, successively, the algorithm was used to convert the surfaces and curves to an analytic form (parametric equations), the data were converted to the environment of industrial robots and formwork was fabricated of polystyrene for complex-shaped industrial concrete members. A set of methods and tools for data conversion and export were tested during the modelling and design of the wall model to check the functionality of the designed procedure. Several sophisticated software applications were also tested in which the optimum formwork was successfully created and verified. The main problems arose during the treatment of the polystyrene-concrete contact interface. Several coating substances, sprays and paints for surface consolidation had been tested during the polystyrene processing and treatment to optimize the surface resistance until the optimum alternative was selected. The support and reinforcing structure was made of plywood boards, by means of this construction the formwork units were fixed and the smoothness of the concrete wall edges checked.

5.1. Additional problems occurred during the research study

- Smooth motion of the robotic device was impaired due to frequent changes in the movement directions: the adopted solution was the approximation of the robot's end tool motion, which led to increased imprecision in the fabrication and a change in the mathematical model. The visual appearance of the member and other technological processes were not affected by this change in any way;
- Ideal smooth polystyrene surface was not achieved: the technology requires further development in order to optimize the choice of used chemical substances for the consolidation and machining of polystyrene surfaces;
- Formwork box stiffness was insufficient causing a slight (in the order of 1-2mm) box strutting and thus an increase in the modelled member due to vibrations during concreting;
- Bubbles and uneven patches can be observed on the resulting member due to insufficiently thorough vibrations of a slender and curved member.

The assumed further development of this technology and designed methods is in the direction of extending the scale and experimenting on actual structures of different types. The RHWC technology can be used for the manufacture of floor constructions, columns, girders and also in the manufacture of non-bearing structural members. The advanced use of the manufacturing technology of units should focus on the exploitation of multiple software applications not only for modelling, but also for reinforcement application, the computation of dynamic and static loading and optimization of the shape of the resulting member, material and dimensions. There is such a curved surface shape achievable that will be more resistant to dynamic loading or more economical in terms of material consumption without compromising its visual appearance. The studied formwork fabrication method is crucial for both further progress in architecture and the production technology of reinforced concrete members. Innovation technologies are becoming increasingly mainstream in the building industry contributing to time and cost savings and offering simple solutions to complicated issues.

Conclusion

The principle objective of the study included: analysis of Czech construction sector and its ability to employ sophisticated automation technologies, the overview of construction sector in general, the key concepts of the Construction 4.0, main applications of robotics in construction, development of architecture and its demands, applying of AM in construction, robotic fabrication of polystyrene formwork for concrete members of complex shapes, and the design and modelling of a concrete wall in the NURBS application. During the modelling and design of the wall model, a set of methods and tools for data conversion and data export, for its treatment and use were verified. Also, several sophisticated software applications were tested from which the optimum option for the formwork fabrication was selected. The main problems occurred during the treatment of the polystyrene-concrete contact interface. A series of coating substances, sprays and paints for the consolidation and surface resistance detection was tested during the polystyrene fabrication and treatment, and the optimum alternative was chosen in the end. The support and reinforcing structure was made of plywood boards, this construction helped to fix the formwork units and the smoothness of the concrete wall edges was verified. The advanced use of the manufacturing technology of units will be based on the exploitation of multiple software applications not only for modelling, but also for the reinforcement, dynamic and static loading and the optimization of shapes, materials and dimensions. The above described formwork fabrication method is crucial for the development of architecture as well as the production technology of reinforced concrete members. Concrete remains a main building material due to its advantages. With modernizing well-established approaches to moulding and treatment of concrete the envelope of monolith buildings will change to be more artistic and complex. Moreover, the applying of sophisticated formwork brings not only aesthetic appearance but also it helps to reduce the amount of material and gives freedom to design optimal shaped structures. Finally, optimal usage of material reduces expenditures, which is very useful to any project. The future issues of RHWC method are to be applied on a large scale monolith structures. In this case, fabrication of the formwork is not the most complicated aspect, but calculating concrete pressure on the EPS formwork, integrating wiring, fire-safety systems and lightening are. Digitation of the fabrication processes leads to determining optimal ways in producing concrete structures to be more rapid, effective and cost-saving.

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