

Politechnika Lubelska  
Wydział Budownictwa i Architektury

# BUDOWNICTWO I ARCHITEKTURA

VOL. 22(1)2023

Politechnika Lubelska  
Lublin, 2022

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Wydział Budownictwa i Architektury

# BUDOWNICTWO I ARCHITEKTURA



**Vol. 22(1) 2023**

Politechnika Lubelska  
Lublin, 2023

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Publikacja wydana za zgodą Rektora Politechniki Lubelskiej.  
Published with the consent of the Rector of Lublin University of Technology.

Finansowana w ramach środków Ministra Nauki i Szkolnictwa Wyższego.  
Financing by the Polish Ministry of Science and Higher Education.

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**ISSN 1899-0665**

Realizacja/Published by: Biblioteka Politechniki Lubelskiej  
Ośrodek ds. Wydawnictw i Biblioteki Cyfrowej  
ul. Nadbystrzycka 36A, 20-618 Lublin, email: wydawca@pollub.pl

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# Use of applications and rendering engines in architectural design – state-of-the-art

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**Abstract:** Computer methods in the AEC (Architecture, Engineering, Construction) industry are constantly evolving, mainly towards BIM, and the design process itself within an investment project focuses mainly on documentation. Visualisation or animation are optional elements, mostly done for sales purposes. Photorealism and the quality of created visualisations influence the impressions of the recipient, and the emotions evoked can determine a purchase or investment. As a rule, designers pay great attention to the visualisations they create, but they are not always aware of the solutions available on the market in this respect. In recent decades, rendering engines based on so-called real-time rendering have developed rapidly. The aim of the study was to provide a deep review of existing 3D modelling and visualisation solutions in terms of their popularity, applicability and advantages and limitations. The focus is on applications working with BIM software, which is widely used in the AEC industry. The paper attempts to compare the applications, lists their advantages, disadvantages, benefits and limitations in their use. The conclusions, sometimes subjective, can be useful for the whole community of architects and engineers, related to space design. The results of the review indicate the increasing popularity of 'real-time' solutions, which are displacing 'offline' solutions.

**Keywords:** building information modelling; BIM application; visualisation software; real-time rendering; AEC industry

## 1. Introduction

Rendering, which can be defined as the process of generating an image based on a specific computational model, is an integral part of creating visualisations. Otherwise rendering is the graphical representation of digitally stored content in an environment-specific form (e.g. display on a computer screen). The part of a computer program responsible for rendering is the rendering engine or renderer. Currently, we can distinguish two approaches used in computer graphics for their preparation: the so-called offline and real-time rendering. The former is a process associated with the traditional path, where

the works performed are extremely detailed and present a look close to photorealism, e.g. thanks to the faithful representation of lighting [1]. However, due to the large number of calculations performed at one time and the considerable hardware requirements, the creation of a single frame through the rendering process itself can take many hours. This excludes the aspect of interactivity, which is the main advantage of the latter approach taking place in real time - where the images displayed on the screen are generated, for example, at a rate of thirty per second. Hence the growing popularity of the 'real-time' approach. Real-time rendering is the process of generating visualisations in a synchronous manner and therefore quick and simple to edit.

Combining the visualization of BIM (Building Information Modelling) with Augmented Reality (AR) offers unlimited possibilities. The prerequisite for the use of AR is the development of suitable applications for mobile devices such as smartphones or tablets, for real-time visualization of 3D digital designs. With AR, we can transfer selected objects such as houses, building elements or interior finishes from the virtual world into the real world using the video stream of mobile devices [2]. There are at least several definitions of visualisation in the literature. In order to define visualisation in an unambiguous way, it is necessary to refer to the purposes for which it is used. In the simplest terms, it can be considered as "the act or process of interpreting a space" [3] and then converting it into a graphic form. It is commonly used as a tool to present designs [4] or concepts, although it can also be important when trying to predict the final appearance of an object before it is realised. It is a kind of bridge between the authors of the plan and the final recipient - client or user - allowing more effective communication. Those unfamiliar with the details of producing technical documentation can make comments by viewing the 3D model or reviewing the non-graphical information (Fig. 1).

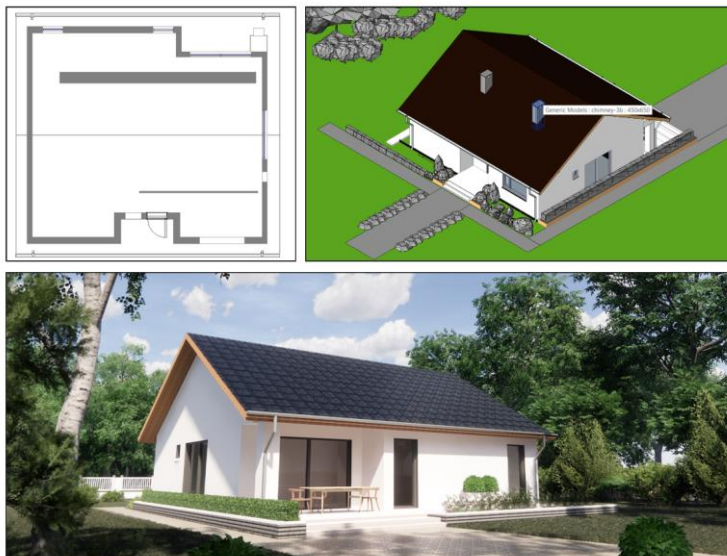


Fig. 1. Comparison of two different views on single-family house design. *Source:* own elaboration.

## 2. Advantages of computer visualization

In late 20th century, architects and engineers stopped using traditional drawing and calculation tools in favour of CAD and later BIM systems [5]. Although individual works drawn with a pencil and depicting a given perspective are still popular due to people's attachment to classical techniques and originality of style, they have been superseded over the years by digital projects as a result of several factors. The first of these is related to costs - specialistic software for commercial use can be expensive, but taking into account the final result and time savings (e.g. by not having to draw each perspective change from scratch), the costs of creating such visualisation for companies are much lower. Apart from the speed of the whole process, an undoubted advantage is also the possibility to introduce changes on the fly and test many variants simultaneously. BIM streamlines the process in terms of the time taken to complete selected tasks, as well as the use, transfer and management of information [6]. With BIM technology, three-dimensional models of existing objects are obtained at different scales [7]. The use of three-dimensional models makes it possible to work with a project at several different stages of its implementation - from initial concepts to more detailed solutions, to have a chance to eliminate potential difficulties. Another advantage of the digital form over the paper form is the visualisation and animation aspect, which allows to present the interiors and surroundings in a more vivid and richer way than in the traditional form. Visualisation and animation tools can be directly linked to the design software, can be installed in the form of "computer farms" - i.e. several regular computers in the same workplace, or they can be made available as a service (Software as a Service). Sophisticated visualisations, fly-through animations or AR (augmented reality) support the decision-making process throughout the investment cycle [8].

## 3. Commonly used software

In relation to the whole visualization process, two types of computer programs should be distinguished - packages used to create geometry, textures and lighting in the whole scene (e.g. 3ds Max) and those using the above mentioned components to create the final image based on a special algorithm or procedure, known as rendering engines. Most often they are integrated with each other within a single product through plug-ins or extensions or, much less often, they work as two independent applications [9]. Due to the fact that there are currently dozens of different products on the market in which projects can be created, also rendering engine manufacturers offer their dedicated versions for multiple platforms simultaneously (Tab. 1).

Table 1. Official availability of rendering engines for design applications. *Source:* Own elaboration.

Software rendering engine	Revit	3ds Max	Cinema 4D	Sketch Up	Blender	Rhino	ArchiCAD
Unreal Engine	✓	✓	✓	✓	✗	✓	✓
V-Ray	✓	✓	✓	✓	✓	✓	✗
Corona	✗	✓	✓	✗	✗	✗	✗
Enscape	✓	✗	✗	✓	✗	✓	✓
Lumion	✓	✓	✗	✓	✗	✓	✓
Octane	✓	✓	✓	✓	✓	✓	✓
Internal rendering engine	✓	✓	✓	✗	✓	✓	✓

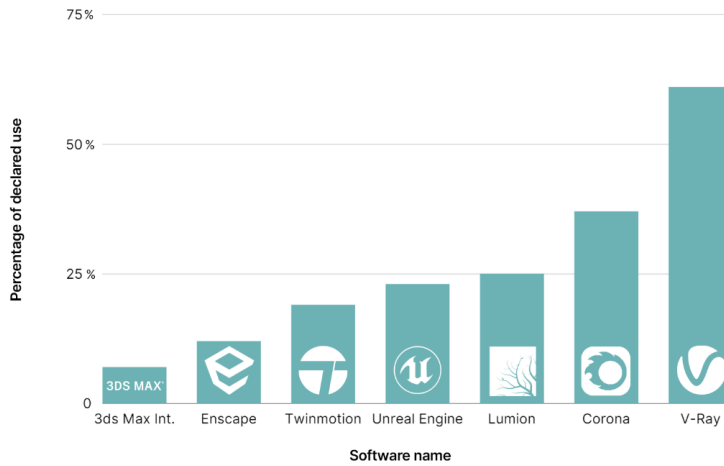


Fig. 2. Popularity of rendering engines among designers in 2021. *Source:* own elaboration.

It is worth noting that in the same ranking, but in a different category (most commonly tested solutions in design studios), engines such as Unreal, Enscape and Lumion are at the top of the table (Fig. 3). Among the most popular solutions, dedicated extensions prepared specifically for BIM-type applications support about half of them, while the process of representing scenes in the remaining ones is sometimes difficult, although not impossible.

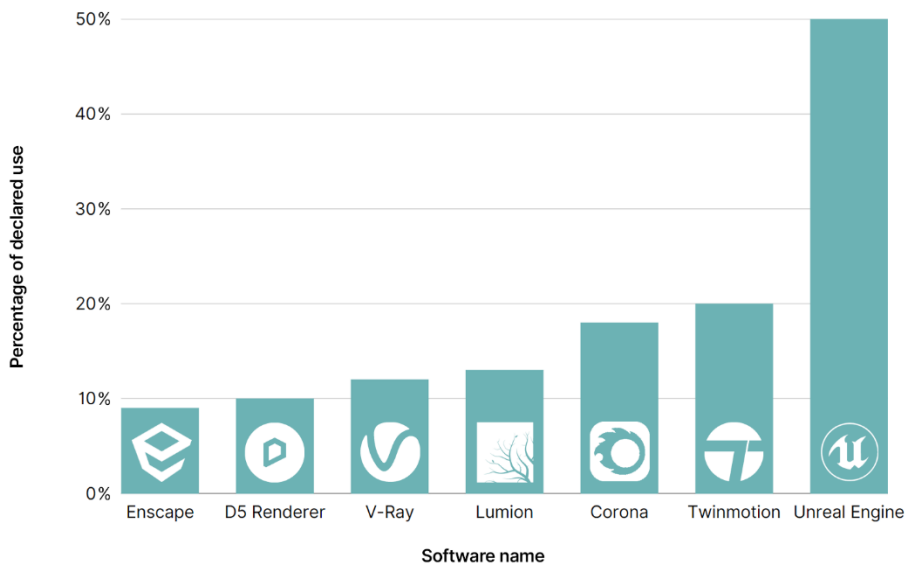


Fig. 3. The most tested rendering engines among designers in 2021. *Source:* own elaboration.

Various organisations have conducted studies on the popularity of using applications in the development process. Visualisation software is used by many professions and industries. On the basis of studies conducted by Chaos Group [10] and NBS (National Building Specification) [11], it can be concluded that programs frequently used for design purposes are, for example, SketchUp, 3ds Max or Revit (Fig. 4).

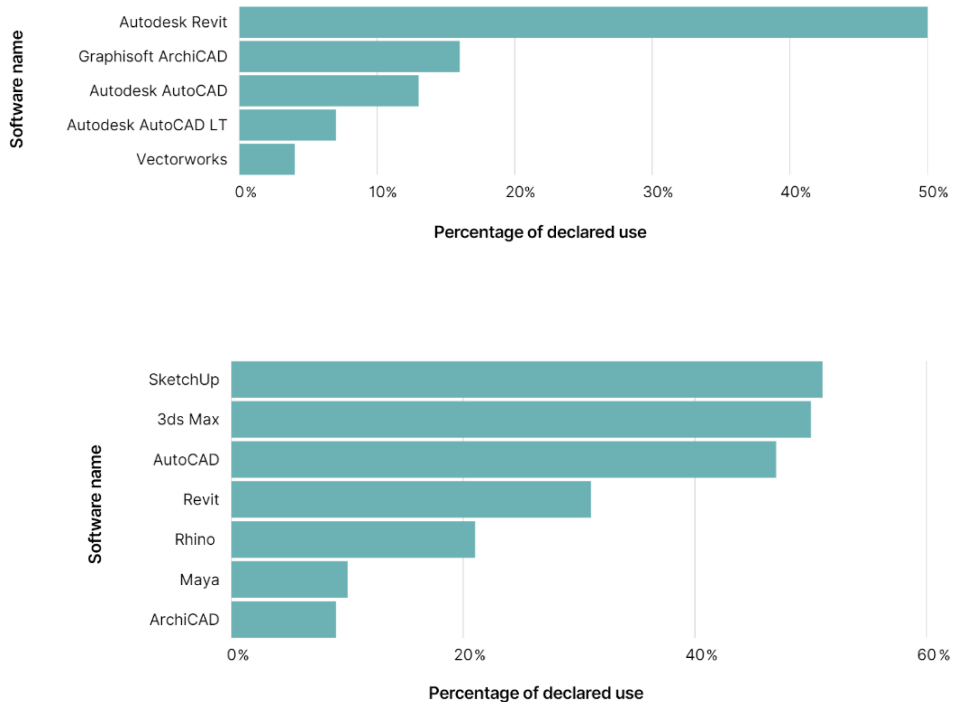


Fig. 4. Popularity of project applications according to NBS report (top chart) and Chaos Group (bottom chart). *Source:* own elaboration.

The multitude of software choices also translates into a very large number of available versions and their distribution models. For example, access to rendering engines is sold as a monthly or annual subscription, or more traditionally, as a so-called perpetual licence, which translates into different product prices depending on their version (Tab. 2). In addition to licences aimed solely at sales aspects, most manufacturers (Enscape, Act-3D, Chaos) offer free versions for students to use for educational and non-commercial purposes.

Table 2. Prices of rendering engines in various forms of sale in PLN (1 EUR = 4,7 PLN) (state as 26.06.2022). *Source:* Own elaboration.

Company/name		Monthly	Yearly	Perpetual license
<b>Act-3D</b>	Lumion Standard	-	-	7 048,00
	Lumion Pro	-	-	14 102,00
<b>Epic Games</b>	Twinmotion	-	-	2 215,56
	Unreal Engine 5	-	-	Free
<b>Otoy</b>	Octane Render Studio	93,96	198,96	-
<b>Maxon</b>	Redshift	211,56	1 242,30	-
<b>Blender Foundation</b>	Eevee	-	-	Free
	Cycles	-	-	Free
<b>Solid Angle</b>	Arnold Renderer	222,00	1 672,00	-
<b>Enscape / Chaos Group</b>	Enscape	187,53	2 250,36	-
	V-Ray 5	258,50	1 480,50	3 337,00
<b>Chaos Group</b>	V-Ray 5 Educational	37,60	418,30	-
	Corona Renderer	187,00	1 316,00	-
	Corona Educational	-	188,00	-

#### 4. Use of BIM in visualisations

Models and scenes made in BIM technology are now increasingly appreciated in the field of interactive visualisation due to the possibility of storing a large amount of information [12]. One of the reasons for this is the fact that parametric modelling makes it much easier to change and edit individual objects added to a scene on an ongoing basis than would be possible with a traditional approach [13]. Visualization, which is created through the rendering process, based on a three-dimensional digital model of a space or a city with its transport infrastructure and all building structures can become a tool in the public participation process. Building digital spatial models is a challenge for many communities [14]. Public and private clients are increasingly demanding dynamic forms such as animation, 360 panoramas etc. in addition to static visualizations. On the other hand, complex semantic databases store information which helps to gain flexibility in planning gameplay, a form of virtual walkthrough or simulations related to the construction of investments (Fig. 5).

In most cases, the most relevant aspect is the entire created geometry of the scene, such as walls or building windows. Usually, when exporting the project to another program for visualisation, the data stored in the 3D models is lost, but this is not an obstacle when creating realistic representations of scenes and the data is not intended to be used in any other way. Scenes designed in BIM technology, e.g. on the basis of an imported geodetic map, are characterised by a very high level of accuracy in relation to real values, which is often difficult to achieve when modelling without references using traditional techniques.

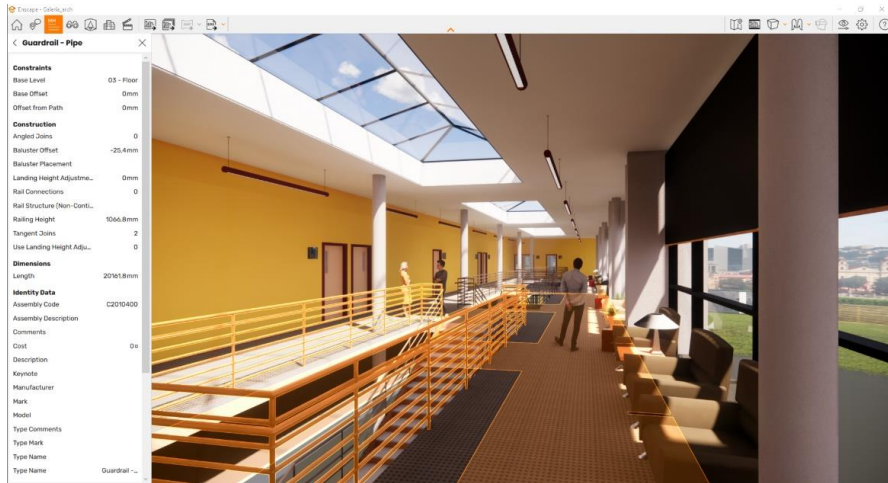


Fig. 5. Showcase of parameters stored in BIM model inside the Enscape engine. *Source:* own elaboration.

## 5. Integration of rendering engines into BIM programs

The process of creating visualisations of projects on the basis of BIM data is most often based on a plug-in created by the manufacturer, which allows to work directly in the program in which the scenes are created or to export data to an external editor - maintaining the connection between them (any change e.g. in Autodesk Revit is continuously transferred and visible in the second window) or not (the case of lack of automatic changes after exporting the geometry and other information) (Tab. 3).

Table 3. Types of integration of individual rendering engines into Autodesk Revit. *Source:* Own elaboration.

BIM software	Rendering engine	Type of integration
Autodesk Revit	Enscape	In program editing in real-time
	Unreal Engine	External editing in a dedicated program without preview of changes in project – necessary re-import of overwritten file
	Lumion	In program editing in real-time
	Twinmotion	External editing in a dedicated program without preview of changes in project – necessary re-import of overwritten file
	V-Ray	In program editing without real-time preview

While the presentation of the scene geometry in each engine is virtually identical, the default issue of the presentation of vegetation created in the project differs greatly depending on the selected software. For example, after importing to Unreal Engine, trees are not replaced by similar models from the existing library, but a simple object that was added in model mode is displayed.

The situation is different in the case of V-Ray or Enscape, where with different effects, but immediately trees are replaced by photorealistic internal library objects.

The basic path for creating grass in Revit is to create a plane representing the terrain and apply a two-dimensional texture to it. As in the example cited earlier - each manufacturer has provided a different way to visualise it:

- there is an advanced material editor built into the V-Ray engine that allows you to create it with specific parameters (Fig. 6),
- using Enscape, 3D grass is presented by default when the material assigned to the model has the "grass" attribute assigned in the appropriate window,
- in Unreal Engine, the plane itself is imported and the grass model and its distribution in the scene are created individually.

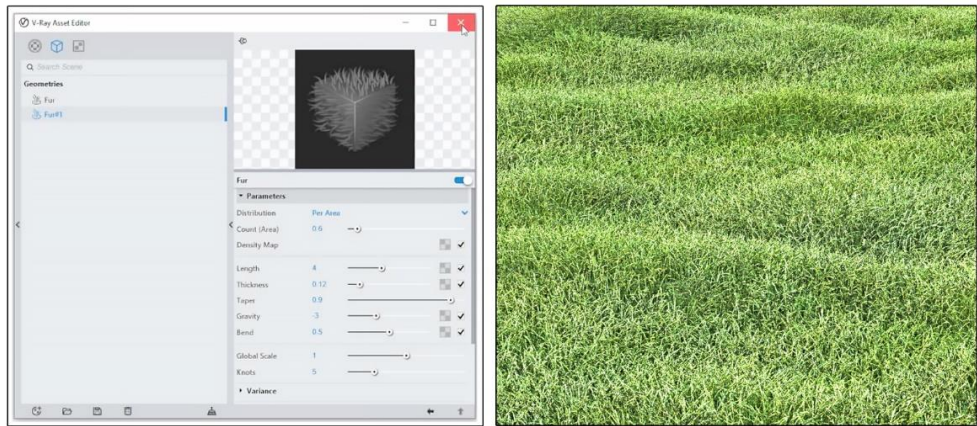


Fig. 6. Creation of grass material in the V-Ray rendering engine. *Source:* own elaboration.

## 6. Rendering in visualisation

In engines such as Unreal Engine or Enscape, what is presented in the internal editor is also the final result, so it is possible to quickly change and re-arrange elements at any stage of its creation. Due to the fact that the development of this technique is largely associated with computer games, many programs that use it allow the user to create, for example, virtual walks, enhancing the immersion of the presentation of projects. Several years ago, the only choice for creating photorealistic images (especially for high-budget films and visualisations of urban or architectural projects) were rendering engines like V-Ray representing an offline rendering approach [15]. This fact was caused, among others, by the hardware limitations of the time, but with the passage of time and the progressive development of technology, the qualitative boundary visible between the two methods is increasingly blurring (Fig. 7). With the announcement of new ray tracing APIs and supporting hardware, developers can easily create real-time applications with ray tracing as a core component (e.g. Twinmotion). As ray tracing on GPUs becomes faster, it will play an increasingly crucial role in real-time rendering. The dynamic development and competition of both approaches (offline and real time) only works to the advantage of the AEC industry [16].



Fig. 7. Example of visualisation using different rendering techniques – Offline (V-Ray) and Real-Time (Enscape). *Source:* own elaboration.

The basis for the development of rendering engines and the modelling and visualisation applications based on them is education. Education at universities not only of design, but also of the tools, will increase the competence of students and later designers in the job market. Practitioners, in turn, will set the direction of software development by reporting further needs. In education, elements of gamification can be implemented, which show greater effectiveness than the traditional approach [17]. The use of modern 3D or virtual reality (VR) technologies in teaching only strengthens the education process for students, who in turn feed the labour market [18].

## 7. Conclusion and discussion

The results of the work show that real-time rendering engines are becoming increasingly popular. The market will move towards dynamic scenes and animations, which customers are increasingly demanding in their projects. The advantages of real-time rendering engines are the speed of editing and the ability to observe changes synchronously. The development of real-time rendering engines has changed the balance of power in the market and is increasingly replacing existing offline rendering solutions. Manufacturers are either defending themselves against the changes or buying up competitors, as was the case with Enscape, which was acquired by the Chaos Group. Users thus have a wider choice of visualisation software and the increasing competition in the market is driving the development of applications. Applications increasingly offer the possibility to export to AR, VR or MR. Visualisation software is not the cheapest, but design studios are aware that its purchase is necessary. The popularity of real-time rendering engines is growing, with successive versions bringing new functionalities (e.g. path tracer in Twinmotion). The price range of the aforementioned applications is very wide, which certainly allows designers from different industries to choose. Regardless of the solution chosen, the end result is always the sum of the user's knowledge and skills.

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# Optimization of the functional concept of the minimum apartment - a study on a selected example. The role of functional details.

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## **Funding**

The research was carried out as part of work No. WZ/WA - IA/4/2020 at the Białystok University of Technology and financed from a research subsidy provided by the Minister of Education and Science.

**Abstract:** The article shows the study about functional concepts of a small apartment. For the research the author has chosen 27,3 m<sup>2</sup> apartment from the estate „Za Żelazną Bramą” in Warsaw. The study works on the optimization of minimum apartment model for 1-2 occupants that could meet contemporary standards. The study has proved that the original layout of the apartment can be improved to bring it closer to contemporary requirements. It turned out that improvements and changes mainly concerned dimensions and arrangement of the kitchen and bathroom. The living space could also be modified – good results have been obtained by implementing innovative details. The last simulation performed in the research (purely hypothetical) showed that the best optimization result could be obtained by slightly enlarging the basic plan of the apartment.

**Keywords:** apartment, flat, functional concept, layout, detail

## **1. Introduction**

For many decades, a large number of small apartments were built in Poland. They can be found in old buildings, as well as in newer housing projects, erected during the economic transformation at the turn of the 20th and 21st centuries. This trend is also visible in the housing market today - small apartments are in great demand. Many of such residential premises do not represent a high level of functional solutions, sometimes requiring reconstruction or correction of the spatial arrangement. Also new apartments – built in the 21st century often require changes to improve their functionality.

The tendency to build small apartments began in Poland before World War II. It was a socially needed housing construction program. After 1945, the Polish government faced the difficult task of building a large number of apartments. The country was ruined, its demographic needs were growing. The Polish state struggled for many years with a large housing deficit. From decade to decade more flats were built, but the housing deficit has not been eliminated to this day. After World War II utility standards of the designed apartments have been set up, and these standards were still in use in Poland until the 1980s. Special provisions have been established in these standards, determining the usable areas of individual types of apartments as well as their percentage share in investments [1][2].

According the research developed by many institutions, e.g. Institute of Urban Development (IRM) in Cracow, Institute of Housing Economy in Warsaw (IGM), Universities of Technology in Białystok, Poznań, Wrocław, etc., the number of 2-room and 1-room flats built in Poland in the second half of 20<sup>th</sup> century accounted for more than 40% of all constructed apartments. The usable area of 2-room flats slightly increased from decade to decade, and in the 1970s it approached the limit of 36 - 44 square meters [3][4].

The introduction of the free market resulted in the suspension of the application of housing design standards and prices of apartments began to be determined by the housing market. The wealth of Poles was gradually growing but prices of flats also were going up. At the turn of the 20th and 21st centuries, the government started the program of building affordable housing for rent worked out by Housing Association Societies (TBS). A kind of housing standard was introduced again, specifying the usable areas of individual types of flats. The search for a minimum type dwelling and the shaping of its functional layouts remains an important problem even today - in the period when the prices of flats have increased significantly and housing again has become less accessible, especially for young people.

The purpose of this research is design analysis, which is aimed at checking the functionality of an apartment with a usable area of 27,3 m<sup>2</sup> and the usefulness of a functional detail in changing the functional arrangement. The analysis will address the optimization of minimum apartment model for 1-2 persons that could meet contemporary standards of life.

There are two main reasons of the flat choice for the study – firstly, the area of chosen apartment (27,3 m<sup>2</sup>) is close to 25 square metres which is the minimum demanded by law regulations in Poland now, and secondly – the flat's layout is based on rectangle without capital walls inside the plan, so it offers the possibility of making changes in the space arrangement.

The author used two methods during research: research by design method and comparative analysis method.

## **2. The state of research concerning functionality of dwellings**

In the process of designing apartments, also small ones, the concepts of functional and spatial layouts play an important role. Valuable solutions are those that allow the so-called flexibility of space and adapting space to the needs of users. This issue began in a house designed by Gerrit Rietveld in Utrecht (Netherlands, where sliding walls were used for the first time dividing a large space into smaller ones [5]. The issue of "free plan" was one of the points of architecture of leading modernists, including Le Corbusier [6] or Mies van der Rohe. In the era of modernism not only the functionality, but also the flexibility of the living space and possibility of making changes began to be features determining the value of housing apartments.

The concept of adaptable apartments is also important in contemporary times, we can see it in some projects (e.g. it has been implemented in housing projects of Ralph Erskine - the Millennium Village development).

In Polish residential architecture, a great contribution to the development of this issue was made by Halina Skibniewska, who designed flexible flats in the Sady Żoliborskie estate in Warsaw [7]. The issues of modernization of apartments and changes in functional and spatial arrangements can be found in the scientific works of Barbara Gronostajska [8]. Many aspects of dwellings functionality connected with flexibility and details we can find in research of Władysław Korzeniewski [9], Monika Magdziak [10] and others. The housing structures for young people and affordable housing have been explored for a few years by Radosław Barek [11] and the author of this text [12]. Aspects of dwelling standards were taken and developed in Poland during transformation time also by Grażyna Dąbrowska [13]. The problem of creating a certain model of a minimum dwelling and adaptable, flexible apartment space remains very important today.

### **3. Research results**

#### **3.1. Case study – the chosen apartment and its location**

As the subject of this research, the author chose the apartment with a usable area of 27,3 m<sup>2</sup> from the estate “Za Żelazną Bramą” in Warsaw, designed in the late 1960s. This housing estate was built in the years 1965–1972 in the area surrounded by Graniczna, Twarda, Prosta, Żelazna, Chłodna and Ptasia streets. The huge area – 63 ha, was completely destroyed by the war in 1943-44. In its place, it was decided to build a housing estate for approximately 25,000 inhabitants. What Le Corbusier could only dream of happened in Warsaw. As many as 75 projects were sent for “Za Żelazną Bramą” housing estate competition. The vision of the team of architects Andrzej Skopiński, Jerzy Czyż, Jan Furman and Jerzy Józefowicz won.

“Za Żelazną Bramą” estate consists of nineteen 15-storey buildings, 5 lower buildings and urban infills. The blocks of the estate were modelled on Le Corbusier's Marseille Unit. Each of the blocks had 15 floors (although lower buildings were also planned), 2 staircases, 2 or 3 elevators and a glazed hall (planned as a meeting place for residents). The modernist concept of a garden city with skyscrapers was very attractive to the Polish authorities at the time, because firstly it was identical with their vision of social equality, and secondly it was cheap and fast.

The skyscrapers were built using monolithic poured concrete. The simple shape of the buildings was rhythmized from the outside by square white plates dividing each apartment and rectangular strips emphasizing the line of windows and closing balustrades (Fig.1).

The estate is located on the north-south axis, so as to guarantee as much sun as possible in the apartments. Many designers' ideas failed to materialize. Each block was to have a recreational roof - with a garden and cafes, grocery stores were to operate on the first floor, the top floor was to function as a laundry and drying room, and the apartments were to have balconies or glazed loggias. Green spaces, schools, kindergartens, nurseries and clinics as well as sculptures standing in parks were planned in the spaces between the blocks. When the estate was built, it was surrounded by emptiness.

The architects of the estate were constrained by DEBOR - the Directorate of Workers' Housing Estates. Skopiński's team, however, fought for their ideas, e.g. a standard of 11 m<sup>2</sup> per person was enlarged - in M2 apartment to about 27 m<sup>2</sup> and in M3 to 38 m [14].



Fig. 1. The building from the estate „Za Żelazną Bramą” in Warsaw – the view. Source: Photo by the author

### 3.2. The original layout of the apartment

The original layout of the M2 apartment - with a usable area of 27,3 m<sup>2</sup>, was based on a rectangular plan with dimensions of approximately 538 cm x 508 cm. The entrance to the apartment has been designed in the middle of the tract. In the area along the corridor there is a small bathroom with a width of a small bathtub (150 cm), on the other side of the narrow entrance hall there is a dark kitchen with the same width of 150 cm, where a sink, a place for a gas stove and a fridge have been designed. The kitchen did not have direct lighting, but it had a window that allowed indirect lighting and serving dishes to/from the living room. The daily zone consisted of a room and a small annex. The apartment is equipped with the so-called "French window" (a door to the entire height of the story secured with a balustrade), a small window in the annex and two horizontal fanlights located high under the ceiling - in the living room and in the annex (they constituted a compositional element on the facade). One heating riser served two radiators. In the space of the living room and the annex, it was possible to set up a sofa or a bed. The spatial layout of the original apartment was rational, but the dedicated areas were small. The small bathroom, measuring 150cm x 195cm, could hardly fit the short tub, sink and toilet. The kitchen also had compact dimensions - 150 cm x 195 cm, in which the arrangement of appliances did not meet the principles of ergonomics (no place for countertop). The annex was narrow, with limited width of 200,5 cm (Fig.2). The apartment does not have a balcony or a loggia.

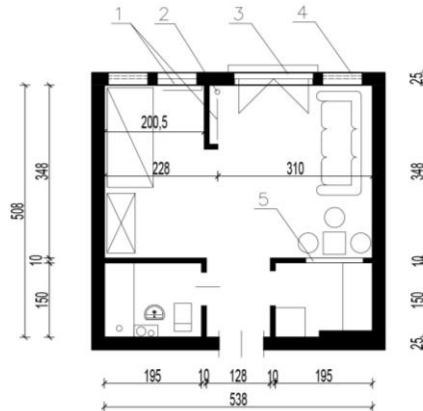


Fig. 2. Apartment from the estate „Za Żelazną Bramą”– original layout. Signs: 1- radiators, 2- heating riser, 3- „French window”, 4 – upper windows, 5 – the window between kitchen and living space. Source: Drawing by the author.

### 3.3. Research variants of functional and spatial concepts

#### Variant number 1

The first variant of the correction of the functional layout consists of following ideas: transforming the annex into a lockable bedroom, in which a wardrobe was added along the entire length of the wall adjacent to the bathroom. The bathroom has been left in its original dimensions. The kitchen space was partially opened to the living room, dividing it into three parts in the proportions of 60 cm - 90 cm - 60 cm. This made it possible to place a refrigerator and a dishwasher under the countertop, as well as to separate a minimum of storage space. A functional detail of U-shaped kitchen furniture was introduced. The living room was arranged as a place to rest and eat meals at a low table, reducing its depth (Fig.3).

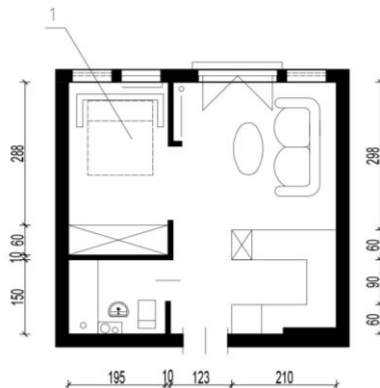


Fig. 3. Apartment from the estate „Za Żelazną Bramą”– functional changes of variant number 1. Signs: 1 - folding bed. Source: Drawing by the author.

### Variant number 2

The second variant of the correction of the functional solution consists of several significant changes of the original concept. In the bathroom, a niche was profiled for setting up a washing machine, breaking the partition wall for planning a wardrobe from the side of the annex. The annex was left open, introducing two functional elements into the wall dividing the space - a sliding wall with a fold-out and unfolding dining table and, on the opposite side of the partition wall, a closed cabinet with a TV set hidden in it, mounted on a hinged arm. This allows for a slightly slanted position of the sofa in the living space. A short clothes hanger has been planned in the entrance hall (Fig.4). The kitchen was solved as in the variant number 1.

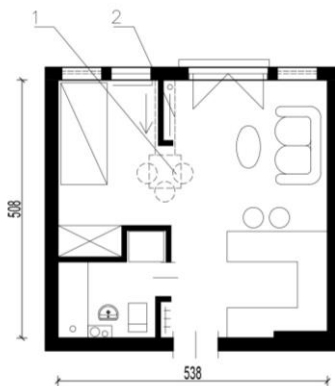


Fig. 4. Apartment from the estate „Za Żelazną Bramą”– functional changes of variant number 2. Signs: 1- moving wall with folding table, 2- TV cabinet. Source: Drawing by the author

### Variant number 3

The third variant of the correction of the original version assumes changes in the kitchen part - the refrigerator is located against the wall, at the entrance on the right side, and the L-shaped tabletop arrangement is finished with an integrated table (small dining space), finished with a rounded, ergonomic shape. In the living space, the sofa was turned with its back to the partition wall, a small work desk was added, while in the annex a movable bed was planned to be folded away from the wall - a kind of functional detail (Fig.5). The bathroom space is planned as in the variant number 2. In addition, the height of the partition wall between the living room and the sleeping annex has been lowered, creating interpenetrating spaces.

### Variant number 4

The fourth variant of the correction of the functional concept introduces other changes. In the kitchen space, the countertops were designed along the inner wall, a short division wall was introduced along the entrance hall, next to which a folded, movable dining table was located. In the living space there are - a sofa, a work desk and a shallow cabinet with a retractable TV on the dividing wall. The sleeping annex is equipped with a bed located along the outer wall, which allowed for free access to a wardrobe, and space for two storage cabinets. In addition, a movable pull-out element was placed behind the desk - after it is pulled out and unfolded, it makes a place to sit along the "French window". There are three movable functional details in total here. The bathroom has a narrow shower instead of a short bathtub (Fig.6).

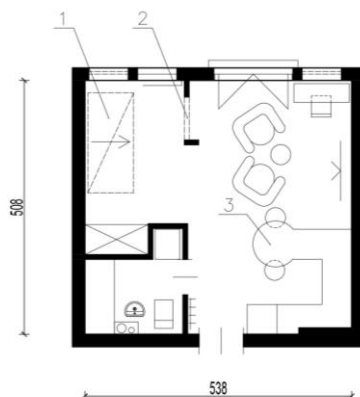


Fig. 5. Apartment from the estate „Za Želazną Bramą”– functional changes of variant number 3. Signs: 1- folding bed, 2- division wall with the hole ( one open space concept), 3- round table integrated with the countertop. Source: Drawing by the author

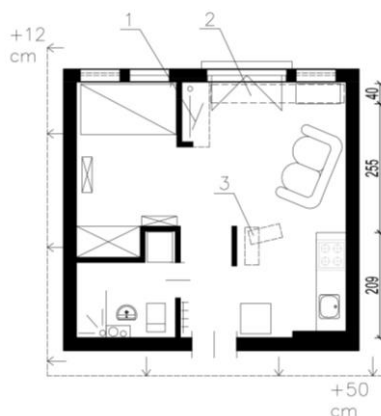


Fig. 6. Apartment from the estate „Za Želazną Bramą”– functional changes of variant number 4. Signs: 1- TV cabinet with angled moving hook, 2- sliding sitting place, 3- moving dining table. Source: Drawing by the author

#### 4. Discussion

The conducted research and design works have shown that the apartment with a usable area of 27,3 m<sup>2</sup> can meet the proper conditions of spatial layout, but there are some problems with good functionality and fulfilling of ergonomic requirements. It should be noted that the original proportions - the apartment was arranged in a rectangular layout with sides of approx. 538 cm x 508 cm - allow to obtain only the minimum solutions necessary in the apartment. A very important role is played by properly designed and dedicated functional details. The usable area of 27,3 m<sup>2</sup> allows the arrangement of a small bathroom, also with the possibility of placing a washing machine, separating a sleeping annex in the apartment with a small wardrobe, planning a living space and a micro-kitchen. The spatial variant works best in an open space model with added functional details.

They make the use of separate spaces multifunctional, and allow for a quick change of space arrangement depending on the user's needs. Weaknesses of all tested variants of the functional and spatial layout are: a short working space in the kitchen (in a case of larger one, there is a loss of the dining space), no balcony and two additional horizontal windows located high (they give little light and cannot be opened from the floor level - they are non-functional). The bathroom in all cases is very small, it has less than 4 square meters of surface – with functionality on low level. It is postulated to increase the usable area of the kitchen and bathroom (apartment in general), because in the kitchen space of approximately 200 cm x 200 cm square, it is difficult to place all necessary devices, to plan the spaces between them and situate a small table. There is no space for a countertop for preparing meals. A certain solution may be a worktop in the form of a bar on wheels (a movable element). The weakness of the functional layout of the apartment is the lack of a balcony. There is only the "French window".

Table 1. Features of the flats' functional concepts - evaluation matrix. Source: the study by the author.

Version type	Strong points	Weak points
<b>Original layout</b>	apartment with usable area and proportions susceptible to functional changes economical communication possibility of separation an annex or a bedroom	very small bathroom non-functional dark kitchen – poor possibilities of work no balcony/loggia small storage area(wardrobe) no place for all devices in the kitchen and for the washing machine in bath non-functional horizontal upper windows
<b>Variant 1</b>	more space in the kitchen for devices (open daily space) longer countertops – better functionality Separation of small bedroom with wardrobe detail: folding bed	small bathroom (original dimensions 150 x 195 cm) no dining area no balcony
<b>Variant 2</b>	additional space for washing machine in bathroom kitchen like above separate annex for sleeping details: moving wall with folding table; TV cabinet	still small bathroom (in spite of enlargement) small space for wardrobe no balcony
<b>Variant 3</b>	details: folding bed, open space flat concept (division wall with the hole); round table integrated with countertop	still small bathroom (in spite of enlargement) small space for wardrobe no balcony
<b>Variant 4</b>	details: TV cabinet with angled moving hook; sliding sitting space next to "French window"; moving bar	small narrow shower in the bathroom (still small area) short kitchen countertop not enough for all devices no larger dining space, only moving table no balcony

Based on the study, it can be concluded that a much better functional result could be obtained if the usable area of the apartment could be increased by 10%, to about 30 m<sup>2</sup> (enlargement of the kitchen, bathroom and storage space could be possible after adding 50 cm to depth, also when 12 cm is added to the width, a regular bed can be put in annex (about 205 cm long) in any position. The dotted line on Figure 6 shows the suggested enlargement of the apartment (on Fig.6). The sketch below shows the results after potential increasing of flat dimensions (Fig.7). Then the proportions of the apartment plan and its functionality become clearly better – new plan dimensions should be at least 550 cm x 558 cm.

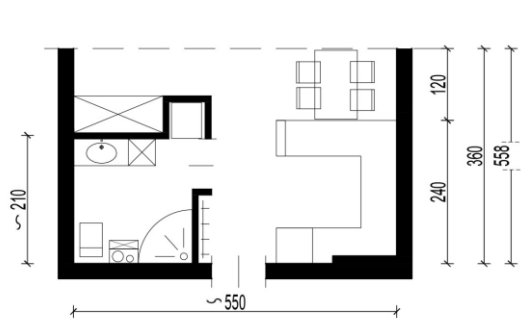


Fig. 7. Apartment from the estate „Za Żelazną Bramą” – after the enlargement of flat’s surface. Possibility of extension of bathroom and kitchen in order to place the contemporary equipment, devices and provide dining area. Source: Drawing by the author

## 5. Conclusions

The study carried out showed that the usable area of 27,3 m<sup>2</sup> allows for functional and spatial layout of the apartment, but only on a certain minimum level, which cannot be regarded as the proper one corresponding contemporary requirements. On the other hand, such surface allows for a certain personalization of spatial concept. The study has proved that such rectangular apartment plan gains more value by introducing various innovative details - the small apartment becomes more functional. The optimal value of the functional layout of this flat with an annex could be obtained after extension of plan proportions - enlargement of the flat (at least 12 cm to its width and 50 cm to its depth). That could help to fulfil contemporary standards. The research proved that the minimum apartment area should be optimized for not less than 30 m<sup>2</sup>.

The results of the conducted research may be helpful in formulating new design standards for the smallest apartments in Poland, it could be useful in designing new apartments as well as during modernization and transformation of existing housing dwellings.

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# Efficiency comparison of mixture formulations in the stabilisation/solidification of the loess silt contaminated with zinc in terms of mechanical properties

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## Funding

This research was supported by “Fly ash as the precursors of functionalized materials for applications in environmental engineering, civil engineering and agriculture” no. POIR.04.04.00-00-14E6/18-00 project carried out within the TEAM-NET programme of the Foundation for Polish Science, co-financed by the European Union under the European Regional Development Fund.

**Abstract:** The effectiveness of various types of binders in stabilizing/solidifying (S/S) contaminated soils is strongly dependent on the type of soil and contaminants present. The literature abounds with studies of stabilisation/solidification of clayey soils, which provides a background for initial assumptions in design of the method application for contamination of this type of soil. However, studies on the stabilisation/solidification of loess silt contaminated with heavy metals are not available. Filling this deficiency is important in order to ensure the rapid adoption of the most effective remedies in case of contamination and their immediate implementation in the subsoil. This paper has enabled the determination of the most effective mixture among the examined for the remediation of loess silt contaminated with zinc in terms of compressive strength. Strengths were determined with the implementation of 30% Portland cement (2.63 MPa), 30% of fly ash-cement mixture (2.21 MPa), an incinerated sewage sludge ash-cement mixture (0.93 MPa)

and mixtures in which cement was replaced by an MgO activator (0.18 MPa for fly ash and 0.63 MPa for incinerated sewage sludge ash). In addition, the determination of strength was carried out for samples containing a mixture of fly ash, activator and cement (0.26 MPa) and incinerated sewage sludge ash, activator and cement (0.26 MPa), with weight ratios of 5:4:1 respectively. In summary, fly ash and cement in a 2:1 ratio can be considered the most effective binding mix in terms of unconfined compressive strength increase.

**Keywords:** loess silt, alternative binder, activator, unconfined compressive strength

## 1. Introduction

Stabilisation/solidification (S/S) is a process that is recognised as a leading remediation method of soil contaminated with heavy metals [1]–[4]. The relatively low cost of its application [5]–[7], time efficiency [8], [9], and most importantly, effective immobilisation of contaminants while increasing the strength characteristics of the subsoil contribute to this. Implementation of various types of binders into the soil in the presence of water causes the hydration process to begin. Simultaneously, various chemical reactions take place, as a result of which heavy metals contaminating the soil precipitate in a less soluble and mobile form, undergo oxidation, chemical reduction as well as mechanical encapsulation in the soil matrix. The above processes immobilising heavy metals can occur individually or collectively, depending on the binder used and the type of contaminant [10]–[12]. Currently, the most commonly used binder in the S/S process, which is cement [13]–[23], has been replaced in significant part by various type of amendments. The reason for these developments is the well-recognised disadvantages of cement, including the uncertain long-term effectiveness of soil binding due to the sensitivity to ageing factors. The aforementioned factors mainly include sulphate erosion [24], the effect of acid rain [25], freeze-thaw cycles [26], drying-wetting and the usual reduction in properties resulting from the passage of time [27]. The negative impact of cement production on the environment manifested in the consumption of natural resources and the formation of a high carbon footprint [28]–[31] is also not ignorable. The above prompts the use of environmentally friendly substitutes for cement, especially in the form of waste materials with pozzolanic properties and various activators and additives that increase the efficiency of the S/S process. It should be kept in mind that no one type of binder can be considered the best for remediating all types of soil contaminated with any heavy metal [32]. In order to obtain the best possible results, binder and additive mixtures should be designed with appropriate proportions that are aimed at the type of soil and the contaminant present, based on existing knowledge from numerous studies reported in the literature [33]. Meanwhile, loess is a very under-researched soil for stabilisation/solidification. There are hardly any data in the publications on the results of studies on the leachability of heavy metals from treated subsoil of this type and its strength. One of the very few studies is the work of Akhter et al. [34], in which the authors determined the leachability of arsenic, cadmium, chromium and lead from loess stabilised with various types of binders, including fly ash, slag, lime and cement. Studies of the strength of stabilised loess [35]–[37], but without the crucial presence of heavy metal contaminants for stabilisation/solidification, do not compensate for this deficiency. Therefore, the authors of the present study attempted to perform stabilisation/solidification of loess contaminated with a selected heavy metal using cement and alternative green binders. The aim of the study was to evaluate the strength of the S/S product after 28 days of treatment using different types of binders and their proportions, as well as to select the most optimal mixture, in terms of mechanical properties. In addition, the performed analysis was used to establish the future research of zinc-contaminated loess silt.

## 2. Materials and methods

### 2.1. Raw materials

The selection of loess as the soil material for the stabilisation/solidification process was determined by the insufficient results of studies of this type in the worldwide scientific literature and the fact that the authors concentrated their attention on testing this type of soil in various geotechnical aspects. The loess (natural water content samples) for the tests was obtained from the area of the left-bank basin of the Bystrzyca River, near Czuby Południowe district in Lublin, from the depth of about 1.5 m below the surface. The location of the sampling point is shown in Figure 1.



Fig. 1. Location of the loess sampling point [based on <https://geolog.pgi.gov.pl/>].

The loess used for the test (denoted as Si) represents a formation of aeolian facies [38]. According to the Unified Soil Classification System (ASTM (2011) D2487), the soil is classified as a low plasticity silty clay (SC-SM) occurring in the subsoil in a solid state, with the grain size and physical properties shown in Table 1. The properties were determined according to ASTM method guidelines [39].

Table 1. Engineering and geo-environmental properties of loess tested.

Property	Values measured	Reference for measurement method
Specific gravity $\rho_s$ [g/cm <sup>3</sup> ]	2.66	ASTM D854
Plastic limit $w_p$ [%]	23.3	ASTM D4318
Liquid limit $w_L$ [%]	29.8	ASTM D4318
Grain size distribution [%] <sup>a</sup>		ASTM D422
Clay (< 0.002 mm) [%]	2.24	
Silt (0.002 – 0.063 mm) [%]	78.64	
Sand (0.063 – 2.0 mm) [%]	19.12	
Soil classification	SC-SM	ASTM D2487
Optimum moisture content [%]	11.82	ASTM D698

The most common heavy metal in contaminated soils [20], while also occurring in the highest concentrations in the natural subsoil [40], is zinc. It represents one of the most soluble metals, with ions characterised by high mobility [41]. Although an essential nutrient for living organisms, it has been shown to be toxic in excessive concentrations [42]. For these reasons, this type of contaminant, introduced in the form of zinc chloride ( $\text{ZnCl}_2$ ) of analytical grade purchased from WarChem, was adopted for the study of loess stabilisation/solidification. The assumed zinc concentration was 0.2% of the dry weight of the soil, i.e. 2000 mg/kg. The feed of the contaminant into the soil-binder mixture was in the form of a solution of  $\text{ZnCl}_2$  inserted in distilled water. The binders used were CEMI cement of 42.5R class (marked with the symbol PC), fly ash from a thermal power station located in Gdańsk (labelled with the symbol FA) and incinerated sewage sludge ash obtained from a sewage treatment plant in Kraków (denoted with the symbol ISSA). The activator used was magnesium oxide ( $\text{MgO}$ , in mixture formulations denoted as M). The chemical composition of all materials is listed in Table 2.

Table 2. Main chemical compositions of the loess, used binders and activator.

	Percentage in weight [%]									
	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	$\text{CaO}$	$\text{MgO}$	$\text{K}_2\text{O}$	$\text{P}_2\text{O}_5$	$\text{SO}_3$	$\text{TiO}_2$	LOI
<b>Soil</b>	72.47	8.26	2.84	4.62	1.22	2.90	nd	nd	0.69	3.77
<b>PC</b>	15.39	2.73	4.18	69.11	0.35	0.57	nd	3.62	0.26	3.28
<b>FA</b>	50.00	20.36	8.00	4.56	1.16	1.89	0.58	1.23	1.44	10.36
<b>ISSA</b>	31.60	6.29	19.62	12.11	3.12	2.11	18.68	1.70	1.17	2.28
<b>MgO</b>	0.99	0.38	12.04	9.42	71.58	nd	nd	0.57	nd	4.27

\* LOI: Loss of ignition; nd: not detected.

A control sample, i.e. loess silt contaminated with Zn not treated with S/S, and test samples to undergo stabilisation/solidification process were prepared for the study. The dry weight addition of binding materials and additives to the dry weight of the soil was determined at 30%. Due to the fact that binder and additive content of the soil dry matter strongly influences the unconfined compressive strength of cured soils further optimisation of the soil/binder ratio need to be performed in future S/S studies. Soil-cement mixes at a ratio of 7:3, soil-cement-ash mixes at a weight ratio of 7:1:2 and soil-ash mixes with an activator at a ratio of 7:2:1 were used for comparison. In addition, a soil-ash mix with an activator and 3% cement content was prepared. The symbols of the samples along with their compositions are summarised in Table 3.

Table 3. Mixture formulations (wt%) of soil, binders and activator samples

	Percentage in weight [%]				
	Loess	PC	FA	ISSA	MgO
<b>100Si</b>	100	–	–	–	–
<b>FA_M_P</b>	70	3	15	–	12
<b>ISSA_M_P</b>	70	3	–	15	12
<b>FA_M</b>	70	–	20	–	10
<b>ISSA_M</b>	70	–	–	20	10
<b>FA_P</b>	70	10	20	–	–
<b>ISSA_P</b>	70	10	–	20	–
<b>30PC</b>	70	30	–	–	–

The mixtures shown above were prepared according to the procedure described in section 2.2 Sample preparation.

## 2.2. Sample preparation

Materials adopted for testing were dried to a constant weight at 105°C for min. 24 h. After drying, the loess was grounded in a ball mill and then sieved through a 2.0 mm screen. The obtained loess silt was combined with selected binders in the weight proportions described in Table 3, and then manually stirred until a homogeneous mixture was obtained. A zinc chloride solution was fed into the mixtures at the assumed concentration until a moisture content of 15% was achieved. All ingredients were again mixed manually until a homogeneous paste was attained. The resulting material was placed in cylindrical moulds (38 mm in diameter and 76 mm high) in three layers with compaction to achieve a final uniform bulk density of the soil skeleton of 1.55 g/cm<sup>3</sup>. After compaction and weighing, the samples were demoulded using a hydraulic press, immediately wrapped in foil and placed in a chamber with a constant temperature of 22°C (±1°C) and humidity of 95% (±1%). The process of stabilisation/solidification of zinc-contaminated loess silt should be considered to have started exactly when the sample was placed in the environmental chamber. The samples were cured for 28 days, which is the most commonly curing time assumed in the literature for comparison purposes. Nevertheless, due to the large influence of the time factor on the final strength of the S/S product, there is a need to analyse the influence of time for the selected mixture formulations in further studies. The above-described procedure, shown in the diagram in Figure 2, was repeated for all presumed formulations. All samples were prepared in quadruplicate.

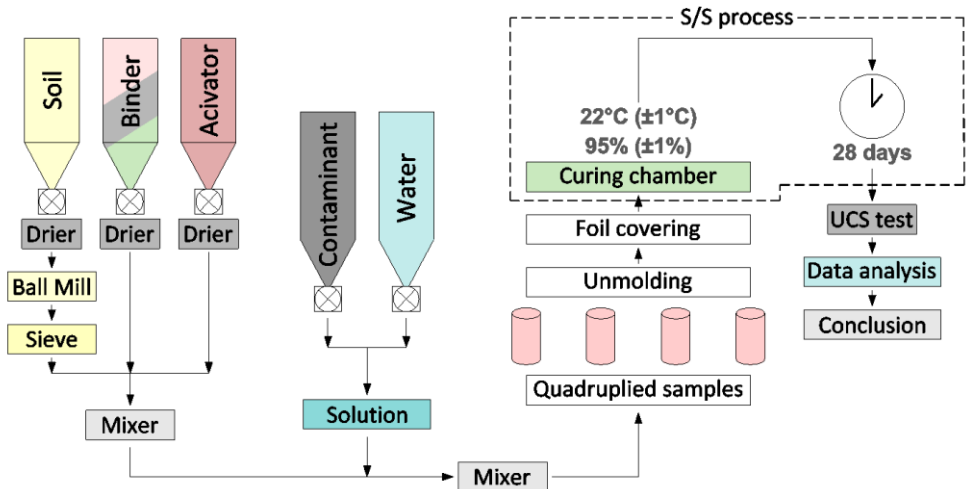


Fig. 2. A scheme of the testing procedure including sample preparation, treatment process and compilation of results.

## 2.3. Test methods

A half hour before the test commenced, the specimens were removed from the climatic chamber and stripped of their foil cover.

The unconfined compression test (UCT) was carried out using the MTS 809 Axial/Torsional Test System at a constant shear rate of 0.2 mm/min, which equates to approximately 0.26 %/min. Each mixture was prepared and tested in quadruplicate, resulting in a final 32 examined samples. After testing, the destroyed specimens were dried

to constant weight to determine the change in moisture content, which decreased from the initial moisture content by 0.8 - 1.4%. Due to the relatively small volume of the samples, it was very important to strictly adhere to the preparation procedure. Exposure to air for an excessive period of time without foil film before being placed in the humidity chamber could have resulted in a reduction in moisture content in the near-surface sections of the sample, with a consequent disruption of the hydration process and subsequent reduction in compressive strength.

### 3. Results and discussion

#### 3.1. Unconfined compressive strength

The performed tests resulted in the compressive strength of the S/S process products using various types of binders after 28 days of treatment. As shown in fig. 3 the obtained values reveal considerable variation.

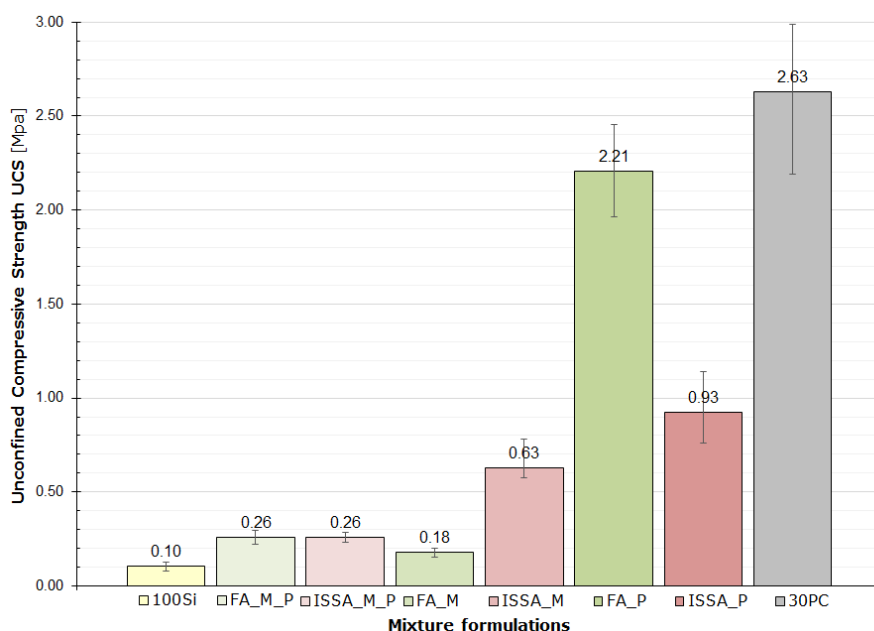


Fig. 3. Unconfined compressive strength of the mixture formulations with use of different binders mixtures after 28 days of stabilisation/solidification process.

All applied mixtures have shown a higher unconfined compressive strength than the untreated soil contaminated with zinc. Product of the S/S process with use of cement presented the highest values, with average of 2.63 MPa. Samples treated with 10% of cement and 20% of fly ash have also demonstrated competitive values, with average of 2.21 MPa. The mixture composed of 70% contaminated soil, 20% ISSA and 10% cement (ISSA\_P) showed a strength 58% lower than the FA\_P mixture, reaching an average UCS value of 0.93 MPa. In light of the aforementioned strengths of the soil-ash-cement mixtures (30PC, FA\_P and ISSA\_P), the results of the soil-ash mixtures with 10% MgO activator appear surprising.

The ISSA\_M mixes, in which the activator was combined with incinerated sewage sludge ash, have shown a strength 32% lower than the ISSA\_P mixes, but at the same time up to 71% higher than the FA\_M mixtures. The FA\_M blends, composed of 70% soil, 20% fly ash and 10% MgO achieved an average UCS strength of only 0.18 MPa, which is less than 2 times the strength of the zero samples. Samples composed of soil, 15% green binder (FA or ISSA), 12% MgO and 3% cement (i.e. FA\_M\_P and ISSA\_M\_P) have indicated an average UCS value of 0.26 MPa.

### 3.2. Stress-strain behaviour.

By analysing the strain-stress relationship curves, it is possible to determine the type of behaviour of the materials in terms of their brittleness. Figure 4 depicts the stress- strain curves of all tested mixtures.

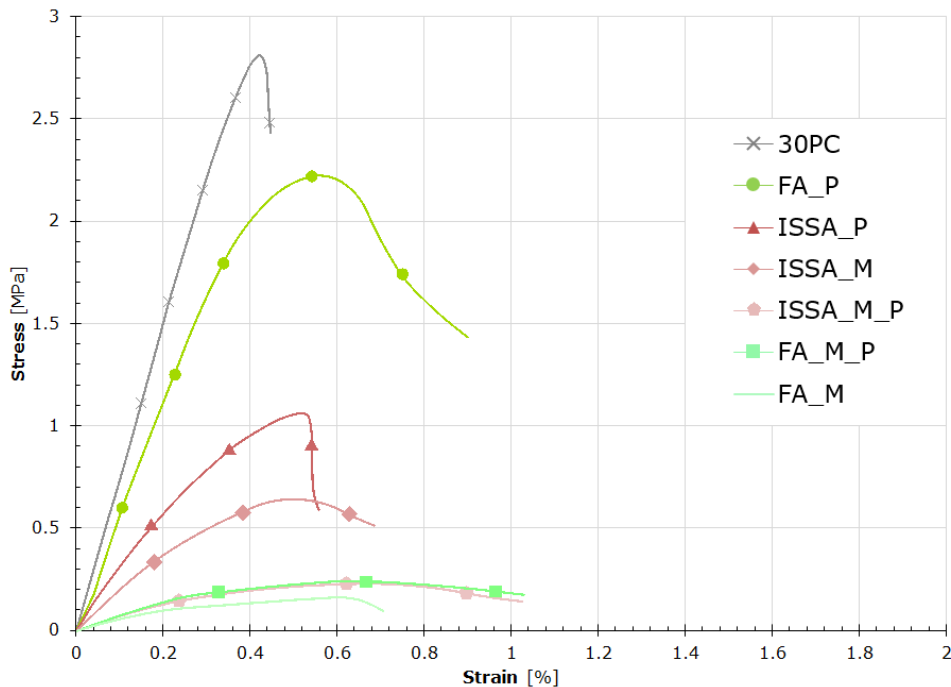


Fig. 4. Stress-strain curves of S/S product with use of different binders mixtures.

It should be noticed, that mixtures present different stress-strain behaviour. The most brittle are mixtures of loess silt with PC and with a composition of incinerated sewage sludge ash and cement. This can be observed in rapid post-peak stress decreasing with any increase in strain. Conversely, mixtures containing MgO are proving to be ductile materials, regardless of the other components. Mixes containing fly ash also exhibit ductility, although in the combination with cement creep is not prominent.

With regard to the results obtained, there is a need to repeat the tests with the ISSA\_M and FA\_M mixes, which showed disproportionate variations in strength with respect to the ISSA\_P, ISSA\_M\_P, FA\_P and FA\_M\_P samples. In order to accurately analyse the results obtained, it is also necessary to determine the chemical processes occurring during

stabilisation/solidification with the individual mixes. This will enable the strength results of the S/S product to be contrasted in the light of microstructural effects. In addition, it is necessary to determine the leachability of zinc from the soil after 28 days of treatment, which, in addition to geomechanical parameters, is the essential part of a stabilisation/solidification process. The introduction of ageing factors (freeze-thaw, drying-wetting, sulphate attack cycles) is also required to determine the long-term effectiveness of the stabilisation/solidification of all designed mixes.

#### 4. Conclusions

The article provides a summary of basic and mechanical laboratory studies carried out for loess silt contaminated with zinc subjected to a stabilisation/solidification process. For the purpose of remediation, the contaminated soil was mixed with different types of binders and the optional use of an activator. According to the results obtained, the following conclusions can be drawn:

1. The highest unconfined compressive strength was demonstrated by contaminated loess silt samples treated with cement. Competitive values were achieved by mixtures with replacement of 2/3 of the cement with fly ash. The unconfined compressive strength obtained were 2,63 MPa and 2,21 MPa respectively.
2. The use of incinerated sewage sludge ash for the S/S process of zinc-contaminated loess silt has been found to be less effective. With combination of cement (in weight ratio 2:1) achieved UCS value was 0,93 MPa.
3. The composition of ISSA and MgO has proven 3,5 times more efficient than FA and MgO in the unconfined compression test performed.
4. The addition of 10% cement per dry weight of all soil additives resulted in an increase in strength for the FA and MgO samples, but a parallel decrease for the ISSA and MgO samples. The strength of the FA\_M\_P and ISSA\_M\_P mixtures averaged 0.26 MPa in both cases.
5. A good correspondence between ISSA and MgO is apparent, and at simultaneously a poor one between FA and MgO. On the other hand, the mechanical properties in the presence of FA are very positively affected by even a minor addition of cement.
6. In terms of unconfined compressive strength with environmental consideration, fly ash and cement in a 2:1 ratio can be regarded as the most effective binder mixture in the light of the tests performed. The reasonably good results of mixtures using incinerated sewage sludge should also be highlighted.

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