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Original Scientific Paper

FOSTERING FLOOD CONTROL POLICY MEASURES AT BASIN SCALE HYDROSYSTEMS WITH THE USE OF GEO-SPATIAL TECHNOLOGIES

UDC 627.51:004.65(495)

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Abstract. *The increased rate of floods occurrence during the last few decades, which is mainly attributed to climate change and mankind pressures on the hydrosystems, results on large scale horizontal flood control and protection policies. At European Union (EU) scale, the Directive on the Assessment and Management of Flood Risks of the year 2007 aims, after implementing sequential processes which amongst other include remote sensing and hydraulic modeling coupling, at proposing specific measures for mitigating the flood risks and the derived socioeconomic devastating impacts. The current research demonstrates the usefulness of geo-spatial technologies for assessing the operationality of the current anti-flood infrastructures together with the historic flood events and the necessity of maintaining the infrastructures. For doing so, all the flood control structures in the case study area were mapped in a geographic information system (GIS). Additionally, information regarding the floods' spatial and temporal placement were used to populate the GIS database, while the repeatability of the works regarding the maintenance and/or restoration and/or failure recovery of the flood control structures was attributed in monetary terms to evaluate the feasibility of the projects. The case study area is the Greek part of the Struma/Strymonas transboundary river basin, which is shared between Bulgaria and North Macedonia and Greece. The outputs of the research demonstrated the usefulness of the current flood protection projects, however, there were particular cases where the annual maintenance cost necessitates the promotion of new and more financial independent solutions.*

Key words: *hydrosystems, floods, geographic information system, anti-flood structures, Strymonas River Basin, Greece.*

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1. INTRODUCTION

Floods are among the most devastating extreme events. During the last 50 years 44% of the weather-related disasters are flood-triggered [1]. The floods have direct impacts on human lives, with approximately 6.8 million human losses to be connected to terrestrial floods during 20th century [2], on national and regional economy, with the direct financial damage of 2002 floods in Prague and Dresden, for example, to be around €20 billion [3], while there are also significant indirect economic effects, such as the cost of economic recovery after a flood [4], on the environment [5], and on the cultural heritage which is either exposed to the outside environment or being part of the interiors of historical buildings [6]. It should be noted that although flood genesis is a natural based process, the imposed radical interventions to the natural environment by humans, e.g. alteration of land uses, technical constructions within flood zones, and river courses alterations, do also play an important role to the increase of floods particularly in urban and peri-urban environments.

Although large-scale floods occur almost every year, it is expected that climate change will increase the frequency and magnitude of these events. Based on the latest Sixth Assessment Report (AR6) on climate change, the more optimistic climate scenario which corresponds to a temperature's increase of 1.5 °C (irrespectively of the utilized model and the socio-economic scenario) foresees more than 50% growth in human losses, approximately 160–240 % of direct flood damage and welfare reduction between 0.23 and 0.29 % [7]. According to the same authors [7], in a 2.0 °C world, a 50% rise of all the negative impacts is expected in comparison to the 1.5 °C estimations. At the same time, the Mediterranean basin is designated as a hot-spot in terms of climate change impacts. The projected temperature increase together with the precipitation spatiotemporal anomalies, i.e. rainfall volume decrease but high-intensity rainfall in short time, is projected to facilitate the occurrence of flash floods, which are characteristic Mediterranean type of floods mainly occurring during autumn in small watersheds and urban areas [8].

The response of the European Union (EU) on the current and projected increased large-scale floods impacts was conducted through the Directive on the Assessment and Management of Flood Risks, commonly known as the Floods Directive (FD). FD aims at reducing and managing the risks of potential floods to human health, environment, cultural heritage and economic activities, and it is implemented through sequential methodological steps, which include the coupling of historical significant flood events with terrain slope characteristics and hydrologic and hydraulic modeling, to produce the Flood Risk Management Plans (FRMPs) [9]. These strategic documents integrate the produced information and propose a list of protection measures that will absorb the flood risk. FRMPs are redeveloped every 6-years to take into consideration any new information and data that could jeopardize the hydrosystem in terms of floods, and to investigate the progress achieved through the adoption of anti-flood measures on designated flood prone areas. At this point it should be mentioned, that although the hydraulic modelling process considers various important hydraulic structures such as bridges, dams, weirs, and diversions, other important anti-flood structures such as culverts, irrigation networks and drainage channels, and gabions, are not evaluated during the simulation process.

At the same time, mature technologies such as satellite remote sensing together with emerging technologies such as the Geographic Information Systems (GIS) have boosted the applicability of hydrological and hydraulic models. GIS, among its other capabilities, combines the storage of descriptive and observational information with coverage characteristics. It can, thus, take advantage of remote sensing products, such as Digital Elevation Models or Landsat images, to provide unique spatial information, as for example the topographic characteristics and the land uses percentage within a basin respectively. These outputs thereafter can be used to define the appropriate hydrological model parameters responsible for the representation of surface runoff the infiltration processes. Currently, both open source and commercial GIS tools are being routinely used, not only for advanced geoprocessing functions but for sharing data across the web via the commonly known WebGIS platforms [10].

The object of the research is to investigate the operationability of anti-flood constructions at a river basin scale through the use of GIS technology and of the Flood's Directive implementation process outputs. For this purpose, flood and water related information, i.e. the historical floods locations, the flood protection structures' locations, and the hydrographic network, together with socioeconomic data, i.e. inhabitant, agricultural and environmental protected areas and related information, were collected, stored and analyzed within an open source GIS environment. Both the inherent analysis of the anti-flood construction figures as well as the spatial analysis of system's features revealed a) the feasibility of the current infrastructures, b) the necessity for supplementary solutions for minimizing the cost of maintenance of the existing flood protection works. The proposed methodology provides a clear and direct assessment on watersheds' flood protection status and can be implemented at basins of various scales.

2. METHODOLOGY

2.1. Case study area

The Greek part, namely the Strymonas watershed, of the transboundary river basin Struma/Strymonas that is shared between Bulgaria, North Macedonia (upstream countries) and Greece (downstream riparian) is the case study area, Figure 1. Administratively, the Strymonas basin belongs to the River Basin District (RBD) of Eastern Macedonia (EL11) and in terms of land uses 52% of the basin is covered from forests and semi-natural areas, wetlands and water cover about 6% of the total area, while the percentage of agricultural areas coverage is also important (42% of the area). Strymonas basin hosts approximately 400.000 inhabitants, with most of them to work on the primary sector, mainly because of the large fertile and irrigated plains of the region [11]. The river flow is regulated by the Lake Kerkini which is located less than 20 km downstream of the borders. This artificial lake was constructed in 1932 as a massive downstream flood protection project, followed till recently by several large-scale land reclamation projects for the irrigation of the basin's plains.

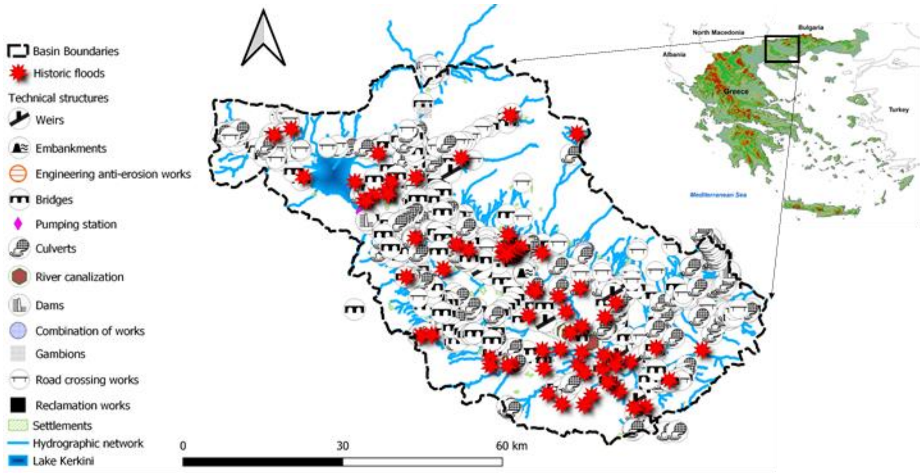

Fig. 1 The Strymonas basin case study area overlayed by the historic floods (red stars) and the flood protection structures.

In terms of water characteristics and floods occurrence, the RBD covers an area of 7,320 km2 and the hydrographic network is consisted of 84 River Water Bodies (RWBs). The Strymonas basin is the larger basin of the RBD covering approximately the whole RBD, thus in the research the Strymonas basin coincides with the RBD extent. The average RWBs' length equals 9.96 km, a length which is very close to the national average length of the designated RWBs, Table 1. Regarding the flood events, the data is separated in two time periods. The first period is up to the year 2011 and includes a limited number of floods, i.e. 93 events at the Strymonas basin and 1627 at national scale, since the national official database for floods' recording and mapping was launched in the year 2012, thus a large number of historic floods is missing. On the other hand, all flood events i.e. 43 events at basin scale, which occurred during the period 2012-2018 have been recorded in the database [9].

Table 1 River water bodies and flood events in the Strymonas basin

RBD	Extent (km^2)	No of RWBs	Average length (km)	Total length (km)	Floods (until 2011)	Floods (2012-2018)
EL11	7,320	84	9.96	837.1	93	43
Greece	131,995	1.317	10.21	13,162	1,627	210

2.2. The QGIS tool and spatial analysis techniques

In the research the development of the platform hosting our spatial database was accomplished with the use of the open-source Quantum Geographic Information System (QGIS) environment. QGIS is a publicly available, open-source, cross-platform and scalable GIS software, which facilitates the development of customised tools, namely plugins, in Python and C++ programming languages [10]. The QGIS operation adopts the standards set by the Open Geospatial Consortium (OGC) and integrates the geospatial data abstraction library (GDAL), which allows it to read and process a large number of raster files of different formats, as well as QGIS supports a variety of vector data formats e.g. PostgreSQL-PostGIS, ESRI shapefiles, GeoJSON, KML, Autocad DXF [11].

Spatial analysis, which is facilitated by GIS platforms, is conducted by coupling techniques of statistics on information that integrate a spatial component, i.e. they have coordinates and are spatially georeferenced. Within GIS by setting the spatial location of an object, the spatial and descriptive relationship between objects, e.g. which antiflood constructions are in a specific distance from an historical flood location and were built after or before a specific time period, were identified. In the research we make use of the aforementioned concept, i.e. we built a number of queries that responded on the spatial and temporal relationship of the floods and on the characteristics of flood protection structures.

2.2.1. Data mining

For the population of the GIS database that we constructed, to perform the spatial analysis techniques and identify the problematic regions in terms of floods, we collected various types of data through various sources as demonstrated in the followings:

Hydrologic/hydraulic data: They correspond to the hydrologic network, the historic floods, the basin and sub-basins boundaries. They are derived from the corresponding River Basin Management Plan and the Flood Risk Management Plan [12-13].

Land uses and environmentally protected areas: The data are related with the types of land and the designation of the areas that have environmental significance. The data are coming from online sources, namely the CORINE land cover programme of 2018, and the Natura 2000 sites designation, respectively.

Flood protection structures and works: The flood protection structures correspond to the geographic locations of the anti-flood structures. The flood protection works corresponds to the number of works that have been accomplished for the maintenance or enhancement of the existing infrastructures. The flood protection works are divided in the following seven categories: 1) weirs cleaning and maintenance, 2) embankments reinforcement, 3) removal of flood-created islands within the river main course, 4) cleaning of bridges' piers from sediments, 5) riverbed deepening, 6) removal of deposits, and 7) other type of maintenance. The data comes after a detailed survey on the flood protection procurement contracts repository of the Water Directorate of the case study region.

3. RESULTS

3.1. Analysis of infrastructure structures and works

The analysis of the survey data regarding the technical structures of the case study area revealed that within the Strymonas basin there have been constructed 649 anti-flood structures. Table 2 depicts both the structures' type and the number of each construction. Most of the structures, i.e. 41.9% or 272 out of 649 projects, are bridges, followed by 185 culvert' constructions, which represent 28.5% of the structures. The third more common flood protection structure, i.e. 17.1% of the structures, is related to road crossing works, while other constructions such as, weirs, dams, and gabions, account for about 2.0%-3.0% of the projects.

Table 2 Recorded technical flood protection structures

Type of structure	Number of structures
Weirs	24
Embankments	2
Engineering anti-erosion works	1
Pumping station	1
Bridges	272
River canalization	6
Reclamation works	18
Construction of gabions	9
Diversions	2
River bed reinforcement	1
Small mountainous dams	3
Culverts	185
Road crossing works	111
Dams	12
Combination of works	2
SUM	649

Most of the anti-flood protection works, as shown in Table 3, are linked to the cleaning of bridges' piers from sediments (55.0%, or 138 out of 253 works). When the repeatability of the works is taken into account, i.e. how many times the same work for the same structure has been repeated throughout the years, the specific percentage is equivalent to 62.0% (431 out of 692 works). The works the removal of the deposits constitute the 11.0% of the total works, with or without considering the repeatability. The analysis of the further data demonstrated that the percentage of the other works is equal to 10.0% or less. The last column of Table 3 presents the average cost per work type, as it was identified (when it as available) in the records of the authorities responsible for the implementation of the specific works.

Table 3 Recorded technical works that are related to the maintenance of enhancement of the existing flood protection structures in the Strymonas basin

Type of anti-flood works	Number of works	Number of works included repeatability	Averaged cost per anti-flood work (€)
Weirs' cleaning and maintenance	4	10	49,750
Embankments reinforcement	16	17	430,870
Removal of flood-created islands	19	19	85,714
Cleaning of bridges' piers from sediments	138	431	49,750
Riverbed deepening	21	44	74,054
Removal of deposits	27	75	47,250
Other work's type	28	96	41,270
SUM	253	692	

3.2. Developed GIS platform

The population of the custom developed geo-referenced system integrated all the collected information, as presented in Table 2. In parallel, a cloud-based version of the geo-reference system (https://gis.consortis.gr/strimonas/) integrating and illustrating all the datasets was also created.

The analysis of the data demonstrated the density of the anti-flood structures, i.e. in which way the structures are distributed within the basin and in which locations the majority of the structures is gathered, Figure 2. Moreover, the overlaying of the historic floods demonstrated the areas which are more flood prone, as well as depict the correlation between floods occurrence and the existence or not of flood protection constructions. The further analysis of the vulnerable areas to floods, i.e. the areas where floods phenomena are frequent, together with the locations and figures of flood protection works revealed the correlation between works and inundation occurrence.

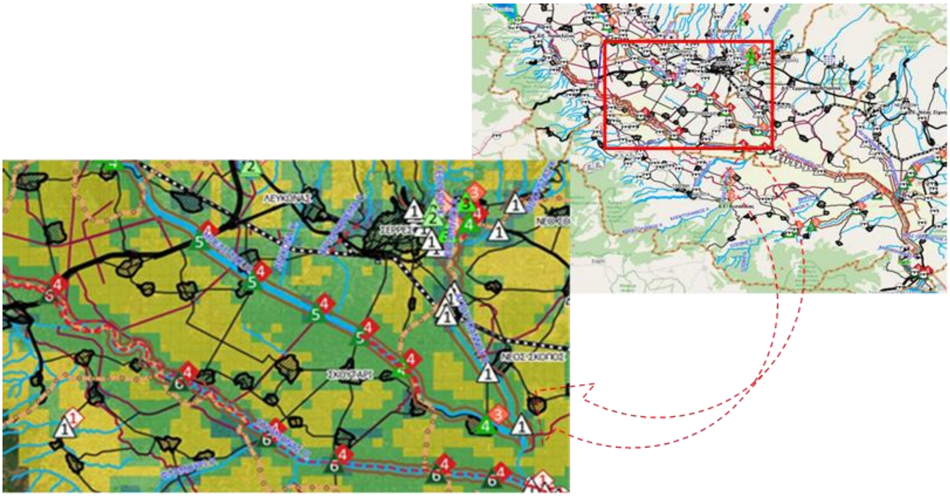

Fig. 2 Case study area as produced within the QGIS environment and zoom in regions with numerous flood protection works (e.g. red triangles and green squares attributes the works of the removal of deposits, and cleaning of bridges' piers from sediments).

4. Discussion and Conclusions

Flood protection plans should not only consider policy frameworks and directives, but also evaluate tangible figures, such as the flood incidences together with the operationality of the anti-flood structures, to assess the necessity of enforcing (or not) the current anti-flood structures and systems. The literature proposes the prioritization of anti-flood works based not only on the financial cost of the structure but also on the coverage of social and environmental prosperity and security respectively [14]. Motivated from the above necessity for sustainable management of floods, the research demonstrated, through the proposed methodology of spatial analyzing flood related elements, such as those gathered and presented in Table 2, that GIS technology can foster the applicability of policies related to flood protection.

The outputs of the research depicted, as expected, that specific regions, within the case study area, with limited flood protection structures had more flood incidents than the ones which were better protected. Moreover, numerous inundations have occurred before the construction of flood protections structures, such as in the case of the region around the Lake Kerkini. Additionally, the research established the operationality of the anti-flood constructions, since the construction of these structures in areas with historic flood events demonstrated that no new floods occurred afterwards.

On the other hand, the analysis of the flood protection works, i.e. actions related to the maintenance or the enhancement of structures and of the hydrographic network, demonstrated the large amount of works that took place in various part of the hydrosystem. Especially, we recorded 253 flood protection works, while by considering the repeatability of specific works, i.e. works that are frequently repeated such as every year or after a significant flood event, we recorded 692 works. This reveals that the average repeatability of the works is up to +153.63%.

Additionally, it was identified that the works have been implemented in 24 river water bodies located within the Strymonas basin. Focusing on the water bodies themselves, it was identified that in the Strymonas River main course have taken place 57 flood protection works. When the repeatability of some tasks is included, the total works amount to 170 works, i.e. a repeatability of +150.44% is presented. In the Aggitis River, which is the larger tributary of the Strymonas River and drains the eastern part of the basin, 36 flood protection works have been carried out. When the repeatability is included, the total amount of work equals 133 tasks, i.e. a repeatability of +137.11% was presented. Finally, in the Belitsa and Krousovitis steams, which are the second most important tributaries of the hydrosystem and practically have the same length, it was revealed that 30 works were carried out in each stream case. However, when the repeatability forms part in the analysis, it was found out that 107 and 90 works have been implemented in each stream respectively, an issue meaning that the anti-flood structures in the Belitsa stream required more often restoration works.

To conclude, as the financial figures of Table 3 demonstrate, there are high annual costs, such as for example the cleaning of weirs and of bridges' piers that account for 7.960.000. The proposal of more permanent and feasible solutions in terms of maintenance, thus, is conceived as the tangible output of the current research. Particularly, the identification of hot spot areas in terms of repeatability of works and high cost for the maintenance of these works, provides useful insights on the management of the flood protection infrastructure.

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REFERENCES

1. Caretta Martina Angela, Mukherji Aditi, Arfanuzzaman Md, Betts Richard et al.: Chapter 4: Water. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 2022.
2. Doocy Shannon, Daniels Amy, Murray Sarah, Kirsch Thomas: The human impact of floods: a historical review of events 1980-2009 and systematic literature review. PLoS Currents, 5, 2013.

3. Kundzewicz W. Zbigniew, Pińskwar Iwona, Brakenridge G. Robert: Large floods in Europe, 1985–2009. Hydrological Sciences Journal, Vol. 58, No. 1, 1-7, 2013.
4. Koks Elco, Thissen Marco, Alfieri Lorenzo, et al.: The macroeconomic impacts of future river flooding in Europe. Environmental Research Letters. 14(8), 084042, 2019.
5. Markantonis Vasileios, Meyer Volker, Lienhoop Nele: Evaluation of the environmental impacts of extreme floods in the Evros River basin using Contingent Valuation Method. Natural Hazards, Vol 69, 1535–1549, 2013.
6. Sesana Elena, Gagnon Alexandre, Ciantelli Chiara, Cassar JoAnn, Hughes J. John: Climate change impacts on cultural heritage: A literature review. Wiley Interdisciplinary Reviews: Climate Change, 12, no.4: e710., 2021.
7. Dottori Francesco, Szewczyk Wojciech, Ciscar Juan-Carlos, et al.: Increased human and economic losses from river flooding with anthropogenic warming. Nature Climate Change, 8, 781–786, 2018.
8. Tolika Konstantia, Charalampos Skoulikaris: Atmospheric circulation types and floods' occurrence; A thorough analysis over Greece. Science of The Total Environment, 865, 161217, 2023.
9. Skoulikaris Charalampos. Toponyms: a neglected asset within the water framework and flood directives implementation process; the case study of Greece. Acta Geophysica, 1-15, 2022.
10. Skoulikaris Charalampos, Ganoulis Jacques, Karapetsas Nikos, Katsogiannos Fotis, Zalidis George: Cooperative WebGIS interactive information systems for water resources data management. Hydrology in a Changing World: Environmental and Human Dimensions. IAHS Publ, 363, 342-347, 2014.
11. Karakos Alexandros, Skoulikaris Charalampos, Monget Jean-Marie, Jerrentrup Hans: The broadcasting on internet of water DPSIR indicators experiment on the Nestos delta, Greece. GLOBAL NEST: the International Journal, 5(2), 81-87, 2013.
12. Special Secretariat for Water. The River Basin Management Plan of Eastern Macedonia Water District (EL11), 1st Revision; Ministry of Environment and Energy, Athens, Greece, 2018. (in Greek, with extended English abstract).
13. Special Secretariat for Water. Flood Risk Management Plan of Eastern Macedonia Water District (EL11). Ministry of Environment and Energy: Athens, Greece, 2018. (in Greek, with extended English abstract).
14. Spiliotis Michael, Skoulikaris Charalampos: A fuzzy AHP-outranking framework for selecting measures of river basin management plans. Desalination and Water Treatment, 167, 398-411, 2019.

RAZVIJANJE MERA POLITIKE KONTROLE POPLAVA NA HIDROSISTEMA SLIVA UZ UPOTREBU GEOPROSTORNIH TEHNOLOGIJA

Povećana stopa pojave poplava tokom poslednjih nekoliko decenija, koja se uglavnom pripisuje klimatskim promenama i pritiscima čovečanstva na hidrosisteme, rezultira horizontalnom kontrolom poplava i politikama zaštite velikih razmera. Na nivou Evropske unije (EU), Direktiva o proceni i upravljanju rizicima od poplava iz 2007. godine ima za cilj, nakon implementacije sekvencijalnih procesa koji između ostalog uključuju daljinsko detekciju i spajanje hidrauličkog modeliranja, da predloži specifične mere za ublažavanje rizika od poplava i posledičnih razornih socioekonomskih uticaja. Sadašnje istraživanje pokazuje korisnost geoprostornih tehnologija za procenu operativnosti postojećih protivpoplavnih infrastruktura zajedno sa istorijskim poplavnim događajima i neophodnošću održavanja infrastrukture. Za to su sve strukture za kontrolu poplava u oblasti studije slučaja mapirane u geografskom informacionom sistemu (GIS). Dodatno, informacije o prostornom i vremenskom rasporedu poplava korišćene su za popunjavanje GIS baze podataka, dok je ponovljivost radova na održavanju i/ili restauraciji i/ili sanaciji kvarova objekata za kontrolu poplava data u novčanom smislu za procenu izvodljivosti projekata. Područje studije slučaja je grčki deo prekograničnog sliva reke Struma/Strimonas, koji dele Bugarska i Severna Makedonija i Grčka. Rezultati istraživanja su pokazali korisnost trenutnih projekata zaštite od poplava, međutim, bilo je posebnih slučajeva gde je godišnji trošak održavanja zahtevao promociju novih i finansijski nezavisnijih rešenja.

Ključne reči: *hidrosistemi, poplave, geografski informacioni sistem, strukture protiv poplava, sliv reke Strimonas, Grčka.*

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Original Scientific Paper

STRENGTHENING OF REINFORCED CONCRETE BEAM ELEMENTS USING ROD-FORM COMPOSITE MATERIALS

UDC 624.012.45
693.557:677.494.7

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Abstract. *The paper emphasizes the advantages of using FRP (fiber reinforced polymer) materials for strengthening reinforced concrete structures. The results of experimental research on the effects of strengthened reinforced concrete beam elements exposed mainly to bending using FRP rod-shaped elements are presented. The load disposition (experimental setup) was in accordance with the "four point load" scheme, and the measurements were made using modern measuring techniques. The results regarding the increase in the bearing capacity of strengthened beams using the NSM (near surface mounting) and EB (externally bounding) methods were compared. In particular, the load-deflection ratio until failure was analyzed, as well as the change in stiffness depending on the load level. It has been shown that the load capacity of beams strengthened with carbon fiber rods (NSM CFRP) increases by 89%, and the load capacity of beams strengthened with glass fiber rods (NSM GFRP) by 73%. The bearing capacity of beams strengthened with EB CFRP laminates increases by 51%. The ductility of strengthened beams was analyzed and it was shown that it is higher when using GFRP rod-shaped elements (DI=6.5) compared to CFRP rods (DI=5.3). The ductility of the beams strengthened by the EB CFRP method was not satisfactory (DI=2.6).*

Key words: *strengthening, NSM method, FRP reinforcement, testing.*

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1. INTRODUCTION

Fiber reinforced polymers - FRP are a type of composite materials, composed of high-strength fibers: carbon (CFRP), glass (GFRP) and aramide (AFRP), which are impregnated with polymer resins (matrix) [1-3]. Along with them, fillers and additives are present in the mixture, giving the required characteristics to the final product. As a result of combining the input components with a special technological process (most often pultrusion), a new material with mechanical characteristics between fibers and resin is obtained. Figure 1 shows the mechanical characteristics of the materials from which FRP materials are made, while Figure 2 shows the mechanical characteristics of FRP composites.

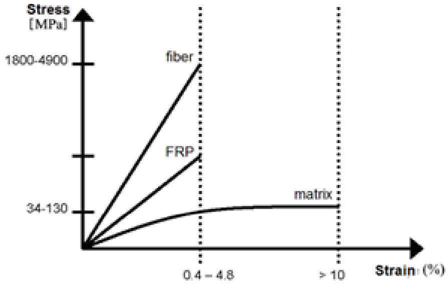

Fig. 1 σ-ε tension diagrams of the basic components of FRP

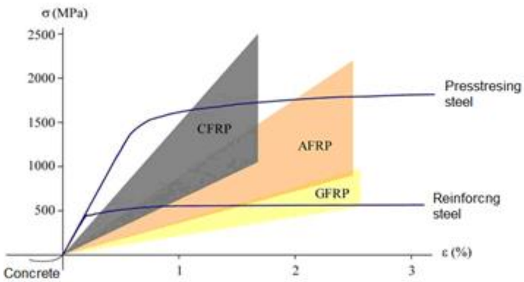

Fig. 2 σ-ε tension diagrams for the most commonly used materials (Pilakoutas, 2000)

The tendency of increasing the use of composites in relation to conventional materials, in almost all areas, is evident. The use of fiber composites as reinforcement in concrete dates back to the 60s of the last century. The reasons for attempts to replace steel reinforcement with non-metallic ones, in concrete reinforcement, lie in the desire to prevent the harmful corrosion behavior due to the aggressive effect, above all, of salt. The first FRP bars were available in the late 70s of the last century, and practical application, as the main reinforcement, in the form of GFRP bars began in 1983 in the USA. FRP products available today for construction purposes are made in various forms: rods, cables, laminates, canvases, nets and three-dimensional elements (Figure 3).

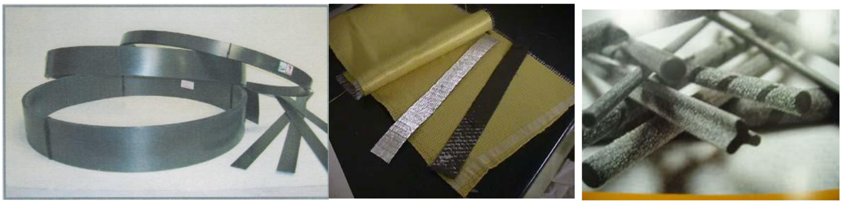

Fig. 3 The shapes of FRP elements: (a) laminates, (b) canvases, (c) rods -‘’bar’’ elements

2. NSM FRP TECHNIQUE FOR STRENGTHENING CONCRETE STRUCTURE

Two basic methods of strengthening concrete structures using FRP elements are externally bonded laminates (EB) and reinforcement placed inside the protective layer of concrete (NSM-near surface mounted FRP) (Figure 4) [4-8].

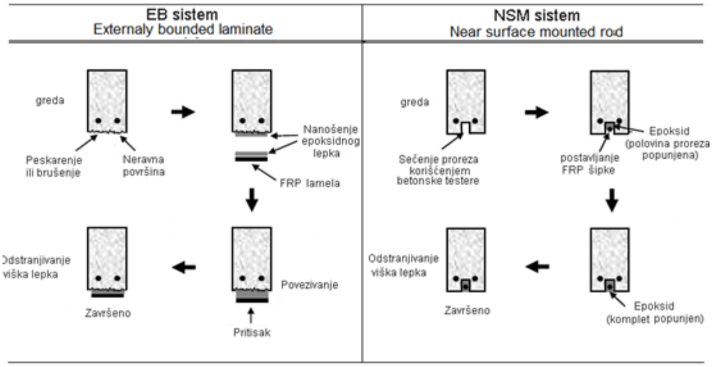

Fig. 4 Procedures for strengthening beam girders exposed to bending using EB and NSM method (Han-Choi, 2008)

Given that the adhesion of FRP elements to the concrete structure has a dominant effect on the strengthening effects and on the possibility of premature failure, numerous studies have shown the advantage of the NSM strengthening method [4-11] in this sense. The basic conclusion of those researches is that the connection properties, i.e. adhesion is influenced by a number of factors: bond length, cross-sectional dimensions of the element, type of he FRP material, cross-sectional shape of the FRP bar, degree of roughness of the FRP bar, strength of concrete (tensile and shear), strength of slot fill (tensile and shear), size, aspect ratio and the height and position of the slits, the degree of roughness of the slits. Due to the large number of influential parameters, extensive research, analytical and numerical, but above all experimental [6-9], was necessary.

In the following, some results of independent experimental research on the application of the NSM FRP strengthening method and a comparison with the EB strengthening technique are presented.

3. Experimental Research

In order to determine the behavior of RC beam girders, strengthened with FRP elements, under the effect of short-term loading, experimental research was conducted on samples in laboratory conditions [12-13].

This experimental analysis includes two variants of application of the additional FRP reinforcement for strengthening RC beam girders exposed to the influence of bending moments according to the "four point load" scheme (Figure 5): 1) installation of the rod-shaped FRP reinforcement inside the concrete protective layer (NSM method) and 2) external gluing of FRP laminate to the concrete surface (EB method). In the research, the FRP reinforcement was used, the composition of which consists of two types of fibers: laminates and rods with carbon fibers (CFRP) and rods with glass fibers (GFRP). An unstrengthened (control) girder was also tested, in order to determine the effects of strengthening and to compare the obtained results.

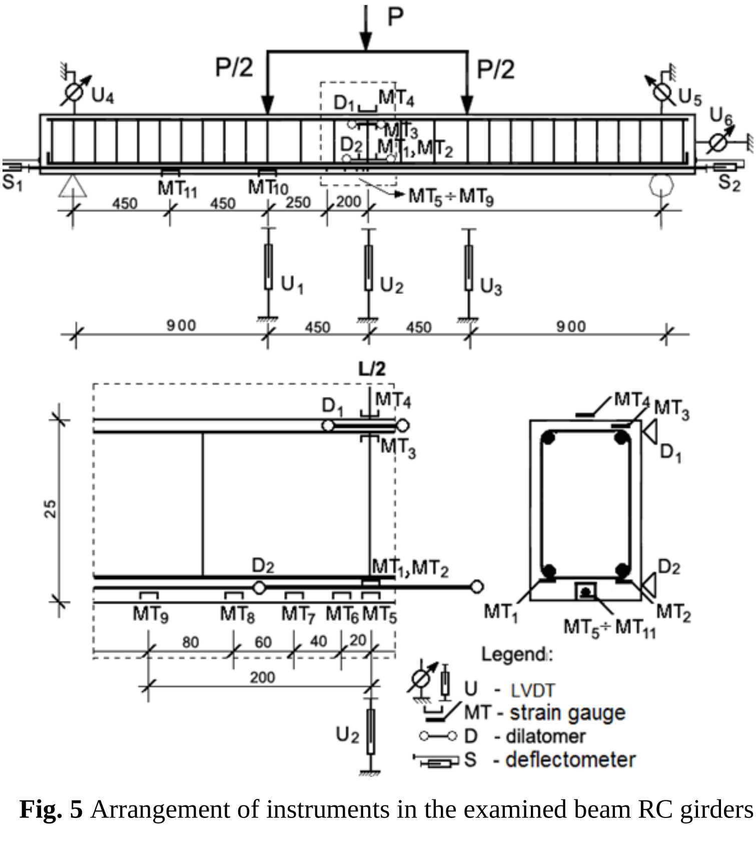

Fig. 5 Arrangement of instruments in the examined beam RC girders

Figure 6 shows the failure mechanism in the externally bonded laminate (EB) method, while Figure 7 shows the failure mechanism in the near surface mounted (NSM) method [13].

Fig. 6 Loss of bond between concrete and epoxy adhesive

Fig. 7 Failure caused by loss of adhesion of CFRP reinforcement

3.1. Analysis of test results

Global deformations (deflection), dilations in concrete, steel reinforcement and FRP reinforcement, slippage of the additional FRP reinforcement, occurrence and development of cracks, all in function of the applied load, were monitored during the loading of the girders. Due to the limited space in the paper, only the results of the load – deflection relations, as integral mechanical characteristics, for the tested variants of strengthening of beam girders are presented.

3.1.1. Deflection analysis

Deflection measurements were performed with linear displacement transducers (LVDT), eliminating the influence of support displacement. Values from the displacement transducer were read every second by the MGC plus acquisition system, using the corresponding "CATMAN" software. This provides a continuous record of the behavior of the beam element exposed to the influence of the test load. For the tested samples, the deformations of the girders under the test load are shown in Figures 8 – 11.

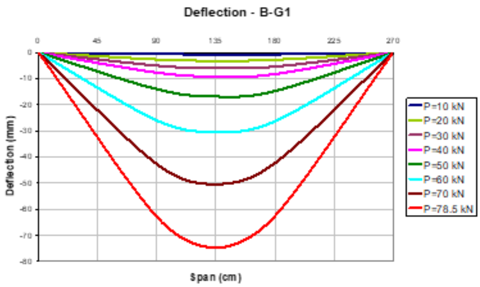

Fig. 8 Deflection of NSM GFRP beam (B-G1)

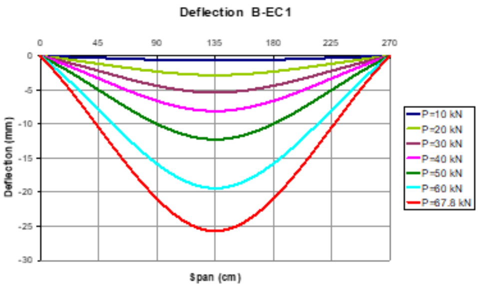

Fig. 9 Deflection of EB CFRP beam (B-EC1)

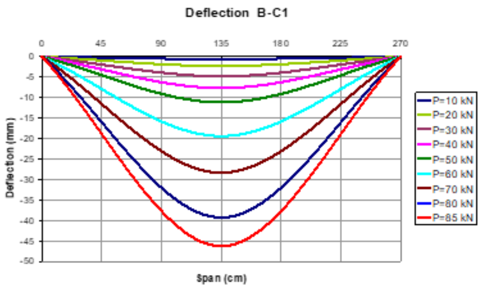

Fig. 10 Deflection of NSM CFRP beam (B-C1)

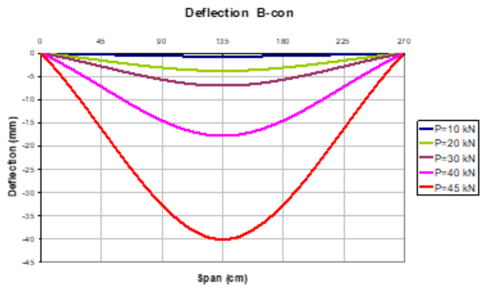

Fig. 11 Deflection of control beam (B-con)

For the purpose of comparative analysis, Figure 12 shows the results of deflections in the middle of the span obtained by testing beam girders strengthened by different methods, with the application of different materials and methods of strengthening. The comparison was made in relation to an unstrengthened (control) beam, where the reinforcement with basic (steel) reinforcement was identical for all beams [13-14].

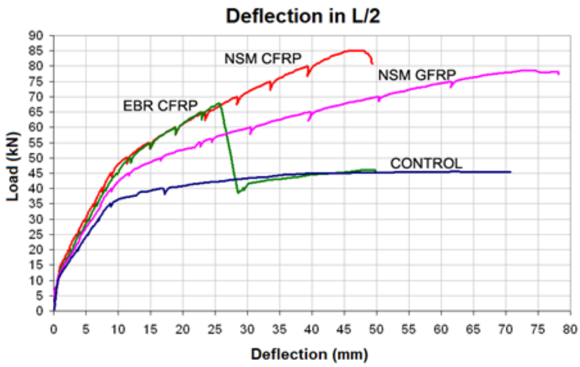

Fig. 12 Deflections in the middle of the span of the examined beams

On the diagrams, characteristic zones can be observed when applying the test load: 1) until the appearance of the first cracks, 2) from the appearance of the first cracks to the appearance of yielding in the basic (steel) reinforcement and 3) from the appearance of yielding of the steel reinforcement to failure. An almost identical behavior can be observed for all tested girders until the appearance of the first cracks, after which the strengthened girders show higher stiffness and higher ultimate load capacity. Debonding of the CFRP laminate in the EB method led to a sudden drop in force and subsequent behavior similar to that of the control beam. By comparing the deflection diagram of RC girders strengthened externally with glued laminates (EB CFRP) and in the protective layer of concrete placed (NSM CFRP), an almost identical behavior is observed until the moment of failure of the laminate by peeling.

A significant increase in load capacity can be observed with the use of the additional FRP reinforcement, which is the highest when the NSM CFRP strengthening is used, where it is as much as 89%. It is noted that the use of the GFRP reinforcement for strengthening gives very good results in terms of load capacity (by 78% higher load capacity), but also the increased deformability (bending) of strengthened girders. Considering the much lower cost of GFRP reinforcement compared to CFRP reinforcement, for cases where the stiffness of the girder is not a limiting factor, preference should be given to GFRP strengthening elements [14].

4. CONCLUSIONS

Based on, first of all, the experimentally obtained results of research on the strengthening of reinforced concrete beam girders exposed to bending to failure, it is concluded that the use of FRP reinforcement leads to a significant increase in the load capacity, stiffness and usability of strengthened beam girders, with the satisfactory ductility.

The experimental results lead to the following conclusions:

The application of composite FRP reinforcement for strengthening RC beam elements exposed to bending is a very effective method, with numerous advantages compared to other methods of strengthening.

Using only one CFRP rod with a diameter of Ø8 mm, when strengthening with the NSM technique, an increase in load capacity by 89% was found.

The beam strengthened with CFRP laminate, with the same axial stiffness as the CFRP bar, showed a 51% higher load capacity compared to the non-strengthened control beam.

With strengthening using GFRP rod with a diameter of Ø10 mm, the ultimate load capacity increases by 73%.

The bearing capacity of beams strengthened with the NSM method is higher than when using the EB method, and the use of CFRP reinforcement gives a higher load capacity compared to beams strengthened with GFRP reinforcement.

The ductility of girders strengthened by the NSM method, expressed through the ductility index (ID), has satisfactory values (ID>4) regardless of the type of FRP reinforcement and is higher when using the GFRP reinforcement (ID=6.5) compared to the application of the CFRP reinforcement (ID =5.3) by 23%.

The ductility of RC girders strengthened externally with glued laminates (EB strengthening method) is insufficient (ID=2.6). In contrast, the NSM method of strengthening shows a significantly higher ductility (ID=5.3), with the same axial stiffness of the reinforcement.

REFERENCES

1. American Concrete Institute, Committee 440 "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures", Farmington Hills, MI, USA, 2017.
2. Fédération internationale du béton (Fib), Bulletin no. 90 "Externally applied FRP reinforcement for concrete structures". Lausanne, Switzerland, 2019.
3. Mapei FRP System, www.mapei.com
4. De Lorenzis, L. and Teng, JG.: “Near-surface mounted FRP reinforcement: an emerging technique for structural strengthening”. Composites: Part B: Engineering, 38, 119–143. (2007)
5. Firas Al-Mahmoud, Arnaud Castel, Raoul François, Christian Tourneur, “Strengthening of RC members with near-surface mounted CFRP rods”, Composite Structures (2009).

6. Tang W.C., Balendran R.V., A. Nadeem, H.Y. Leung: "Flexural strengthening of reinforced lightweight polystyrene aggregate concrete beams with near-surface mounted GFRP bars", Building and Environment 41, 1381–1393, (2006).
7. Nanni, A.,. "North American Design Guidelines for Concrete Reinforcement and Strengthening Using FRP: Principles, Applications, and Unsolved Issues," Journal of Construction and Building Materials, Vol. 17, No. 6-7, pp. 439-446. (2003)
8. Bilotta, A., Ceroni, F., Barros, J. A. O. , Costa, I., Palmieri, A., Szabó Z. K., Nigro, E., Matthys, S., Balaz, G., Pecce, M. "Bond of NSM FRP-Strengthened Concrete: Round Robin Test Initiative", Journal of Composites for Construction, 20(1), pp. 4015026-1–4015026-16, 2016. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000579
9. Kadhim, M. M. A., Jawdhari, A., Peiris, A. "Evaluation of lap-splices in NSM FRP rods for retrofitting RC members", Structures 30, pp. 877–894, 2021. https://doi.org/10.1016/j.istruc.2021.01.054
10. Shadravan, B., Tehrani, F. M. "A Review of Direct Shear Testing Configurations for Bond between Fiber-Reinforced Polymer Sheets on Concrete and Masonry Substrates", Periodica Polytechnica Civil Engineering, 61(4), pp. 740–751, 2017, https://doi.org/10.3311/PPci.9090
11. Taljsten B, Carolin A, Nordin H.: "Concrete structures strengthened with near surface mounted reinforcement of CFRP", Adv Struct Eng. 6(3):201–213, (2003).
12. Coelho, M. R. F., Sena-Cruz, J. M., Neves, L. A. C. "A review on the bond behavior of FRP NSM systems in concrete", Construction and Building Materialsn 93(15), pp. 1157–1169, 2015. https://doi.org/10.1016/j.conbuildmat.2015.05.010
13. Rankovic S., Folić R., Mijalković M.: Efects of RC beams strengthening using near surface reinforced FRP composites, FACTA UNIVERSITATIS,Vol8, N°2, (pp. 177-185). (2010).
14. Ranković, S., Folić, R., Mijalković, M. "Flexural behaviour of RC beams strengthened with NSM CFRP and GFRP bars – experimental and numerical study", Romanian Journal of Materials, 43 (4), pp. 377–390, 2013.

OJAČANJE ELEMENATA ARMIRANO BETONSKIH GREDA PRIMENOM KOMPOZITNIH MATERIJALA U OBLIKU ŠIPKI

U radu su istaknute prednosti upotrebe FRP (fiber reinforced polymer) materijala za ojačanje armiranobetonskih konstrukcija. Prikazani su rezultati eksperimentalnih istraživanja uticaja ojačanih armiranobetonskih grednih elemenata izloženih uglavnom savijanju korišćenjem FRP šipkastih elemenata. Raspored opterećenja (eksperimentalna postavka) bio je u skladu sa šemom „opterećenja u četiri tačke", a merenja su vršena savremenim mernim tehnikama. Upoređeni su rezultati u pogledu povećanja nosivosti ojačanih greda primenom metoda NSM (near surface mounting) i EB (external bounding). Konkretno, analiziran je odnos opterećenje-ugib do loma, kao i promena krutosti u zavisnosti od nivoa opterećenja. Pokazalo se da se nosivost greda ojačanih šipkama od ugljeničnih vlakana (NSM CFRP) povećava za 89%, a nosivost greda ojačanih šipkama od staklenih vlakana (NSM GFRP) za 73%. Nosivost greda ojačanih EB CFRP laminatima povećava se za 51%. Analizirana je duktilnost ojačanih greda i pokazano je da je veća pri upotrebi GFRP šipkastih elemenata (DI=6,5) u odnosu na CFRP šipke (DI=5,3). Duktilnost greda ojačanih metodom EB CFRP nije bila zadovoljavajuća (DI=2,6).

Ključne reči: *ojačanje, NSM metoda, FRP armature, ispitivanje.*

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Review Paper

ACTIVE MOBILITY AS AN ALTERNATIVE FOR THE DAILY COMMUTE. ISSUES AND CHANCES FOR THE CITY OF VARNA

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796.61(497.211

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Abstract. *There is a variety of synonyms to describe the transport of people that only use their physical activity for the need to travel, and active mobility is most commonly-used. Soft mobility, human-powered mobility, active travel, active transport, active transportation and active commute are also in the list. And beyond all doubt the most popular forms are walking and cycling.*
The current paper explores some problems of active mobility, regarding the need for sustainable daily commute. In this point having sustainable alternatives to private motorised transport is vital for the development of settlements but often the importance of soft mobility in their connectivity with industrial areas is underestimated. Using active forms of transport, mainly bicycle and pedestrian traffic, as well as a combination of them and public transit, is a chance to make urban spaces more livable.
Many areas are difficult to be accessed without personal motorised transport and for the city of Varna the adjacent resorts and industrial territories are such a striking example as their connection with the rest of the settlement is full of barriers to cycling and walking commute.
In this paper, regarding its topic, the author explores some issues that people face every day in the city of Varna and searches chances for future improvement based on a good practice example from Barcelona.

Key words: *active mobility, daily commute, industrial areas, transport connectivity, sustainability.*

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1. INTRODUCTION

For decades and centuries of development the predominant means of transport of the settlements have changed, as well as the type, density and dimensions of the street network. Undoubtedly, over the last five decades, urban mobility has become one of the greatest challenges for the development of modern cities and critical factor for both the positive and the negative attributes of urbanization [1]. Therefore, growing mobility is crucial for cities but it should be resilient growing in order to avoid the associated issues and shortcomings. Present day and future cities' mobility has to be sustainable in order to reduce the negative environmental and social impacts. As planning our towns and cities is becoming more and more complex urban mobility should also be regarded as a complex system involving a number of modes of transport with a large variety of effects, typical of complex systems.

During the 20th century transportation modes and systems have undergone significant changes. According to the figures in Oldenziel and de la Bruhèze's paper [2] changes began in the 1950s with the rapid increase in car ownership and the rapid decline in bicycles' share in total number of trips. „In postwar reconstruction, the nation states in Europe all reinforced the shift toward anti-cycling sentiments and pro-car attitudes" [2]. As a result of the dominance of private cars in our everyday life pedestrians and cyclist have been neglected for several decades. The importance of pedestrian connectivity was put into place ever since the beginning of 1960s by the American urban theorist Jane Jacobs. The 1970s mobility protests in the Netherlands helped stop a rapid decline in cycling rates between the 1950s and the 1970. But it took time for those efforts to gain momentum. Active mobility concept was put in the daily agenda at the end of the 1980s and continuing into the 1990s, although proposed using a variety of terms. Active mobility, soft mobility, human-powered mobility, active travel, active transport, and active transportation, active commuting are all synonyms. They are used to describe transport of people which only use the physical activity of humans for the need to travel. Regarding the latest walking and cycling are definitely the most common forms of active mobility.

The current paper explores active commuting, regarding the need for sustainable transport connectivity between different functional units of settlements, including industrial parks and territories and resort areas. The emphasis is on the possibilities for realizing more of the business trips, using active forms of transport, mainly bicycle and pedestrian traffic, as well as a combination of them and other means of public transport.

The starting point of this study is that active commuting, encompassing modes of transportation such as walking and cycling, holds significant potential to revolutionize the daily commute landscape and address pressing urban challenges. By prioritizing active mobility options over traditional vehicular modes, cities can potentially mitigate traffic congestion, reduce air pollution, enhance public health, and create more vibrant, sustainable urban environments.

The main goal of this research is to make a brief overview of the general aspects of active mobility, including the historical aspect of the topic and the difficulties of changing people's habits regarding the use of private cars. By presenting the city of Varna's negative experience and Barcelona Metropolitan Area's good practice with Bicivia, the author seeks to draw the attention of a wider group of people to the requirement for planning and executing measures to better the active connectivity in the city of Varna, with a particular focus on the industrial and resort areas.

2. METHODOLOGY

The current study is intended as an overview in terms of active mobility, evolution of transportation, the travel time budget concept and active commute. It also presents the current situation in the city of Varna with the good practice of Bicivia project.

In relation to the above, methodology is based on qualitative research and case study research:

- Literature review and conclusions on the benefits, challenges and importance of mobility and connectivity for the existence of urban organisms;
- Literature review and conclusions regarding the evolution of urban transportation and the role of travel time budget in urban mobility and connectivity;
- Literature review and conclusions on the place of active mobility in the urban transportation system as well as the benefits, concerns and importance of active commute;
- Review of case studies related to the negative practice of the city of Varna and the successful project Bicivia in Barcelona.

3. ACTIVE MOBILITY AND CONNECTIVITY

In their report "An integrated perspective on the future of mobility" Hannon et al [3] consider mobility as vital part of our everyday life, in fact they call it "the lifeblood of our cities". It is essential for urban life, for bringing people to and from work, children to and from school and kindergarten, and the way people move around the urban environment is primed for dramatic change.

To view a city from above is to observe a world in motion. Urban transit carries people to and from work; private cars and taxis circulate in abstract patterns; urban freight deliver goods; pedestrians hustle through city blocks; cyclists zip through traffic. Mobility matters to people, whether this is getting to work or school with ease, visiting friends and relatives, or simply exploring the surroundings. In relatively few places, however, does the reality of what is available match the public's aspirations for safe, clean, reliable, and affordable ways to get from A to B—and back again [3].

In his paper from 2006 "Cities Can Save the Earth—The Urban Solution to Climate Change, Species Extinctions and "Peak Oil"" [4] Richard Register draws readers' attention towards one big problem that has to be solved in the future: "Designing cities around something that weighs 3,600 pounds instead of whatever you weigh, is something that needs to change." Thinking about the last the author believes that with few exceptions such as the Netherlands and Denmark, the world has not reached very far towards establishing the city for active mobility.

Planning and building cities for providing sustainable mobility, connectivity and accessibility is one of the major requirements for having sustainable and resilient urban organisms. Walking, as also cycling, is a multi-purpose and multi-sensory experience. In order to have safe, convenient, comfortable and delightful walking and cycling experience a consistent and pleasant design is needed. It would encourage active mobility as a popular commuting means, as well as an attractive recreational option. In order to develop a city suitable for walking and cycling we have to consider cycling and pedestrian paths to be direct, safe, comfortable and attractive. And it is essential to think of every place in the city, every neighbourhood, street, square or park space.

In the context of sustainable and ecological planning, mobility, as a human characteristic, is expressed in the provision of an opportunity to reach the greatest number of goals in a short amount of time. The latter should be located at a minimum distance, because quickly reaching them is more a function of their compact layout than of the speed of movement. In urban planning, accessibility is defined by the time required to reach the intended goals. This means that as the distance increases, we need to increase the speed of movement to achieve maximum accessibility.

Taking into account the inherent disadvantages of urban transport, the uneven distribution of personal motor vehicles and the basic requirements for sustainability (including minimal pollution and energy consumption), it turns out that the solution lies in bringing the centers of attraction closer to us, not in increasing the speed of movement. And so it turns out that sustainable accessibility is expressed in the provision of closely located quality goods and services in combination with high-quality ecological transport links (direct, attractive pedestrian and bicycle paths and attractive public transport) [5].

3.1. The evolution of transportation and the travel time budget

“A city is as big as the speed allowed by its transport system.” A short and very meaningful thought by David Lindelöw [6], describing in few words the historical relationship between city’s shape, form and structure and the transportation. The urban street network is known to be the backbone and the circulatory system of any settlement and as such it is vital for the existence and the development of urban organisms.

The evolution of transportation systems was among the main driving forces that lead to changes in settlements’ size, form and land use patterns. New traffic and transportation systems emerged over the years and formed the basis of new and more complex urban systems building on top of the original walking city fabric [7].

The boundaries of the ancient cities were limited by the predominant means of transportation. The radius of development was defined by the approximate walking distance within 30 minutes, and it was not much than 2 kilometers. In the pre-industrial age, commuting from a rural estate to a job in the city was not possible on a daily basis [8].

During the industrial revolution new forms of transportation appeared and with the emergence of the steam powered public rail it was possible to live in the suburbs, further away from the workplace. Having this faster transportation, it was already possible to commute to about 16 kilometers within the 30-minute isochrones.

The first mass urban transport, the omnibus, appeared in the form of a horse-drawn passenger wagon in 1826 and was the first land-based innovation in public transportation.

Afterwards, in the late 19th century, bicycles and electric streetcars created a revolution in urban travel. The operating speed of electric trolley was three times faster than that of omnibus and did not generate wastes. In practice, streetcars and bicycles could cover more than 6 kilometers in half an hour. And with the help of the elevated trains (in USA) and the underground network (in Europe), already at the end of the 19th and the beginning of the 20th century cities were able to spread outward 20 to 30 kilometers.

In the second half of the 20th century, the massive diffusion of the automobile, as well as the construction of highway networks, had substantial impacts on urban mobility and urban street network. Highways were built to connect the urban core to the periphery and, in many cases, complete or partial ring roads were built. The mobility freedom offered by the private car represented a paradigm shift in terms of lifestyle, consumption patterns, as well as residential locations. The car on the freeway enabled large numbers of people to travel long distances on a day-to-day basis. Within a short period, the automobile became the dominant mode of travel in most cities around the world. Instead of small railroad suburbs, where housing was restricted to a short radius around stations, with the presence of private cars and the highways drivers could now commute more than 30 km in 30 minutes. If the streetcar city covered 80 square kilometers, the 60-kilometer-diameter expressway city could cover over 2000 square kilometers [8]. The automobile reduced the time for traveling considerably, but together with its positives it caused many problems in people's daily live. Motorization and the diffusion of personal mobility have been an ongoing trend linked with substantial declines in the share of public transit in urban mobility [9].

Regardless of all the evolution in transportation and the growth of our towns and cities, the “travel time budget” remains relatively stable throughout the years - getting to work still takes average about 30-35 minutes.

Having in mind that “time is money” forces us to think on a larger scale how (and if) travel time can be saved. Contemporary planning ideas such as densification, mixed-use development and urban renewal are all measures that can increase the proximity between destinations in cities – and should thus be treated as time-saving policies, as are “traditional” investments in transport infrastructure. However, such measures are rarely labelled as investments in transport infrastructure. Moreover, the focus on minimizing travel time almost automatically excludes pedestrians and cyclists, whose options for increasing speeds is naturally limited [6].

So, with the help of a proper infrastructure and policies, and a fast and convenient mass urban transport active mobility means could also be a more substantial part of peoples’ choice for commute.

3.2. The active mobility subsystem

Today’s towns and cities, especially bigger ones function as complex macrosystems that contain smaller units, for example the neighbourhoods. An essential condition for the territorial and demographic growth of cities is the presence of convenient transport access between their units and to local and historical centers [10]. Time is regarded to be a major index for measuring connectivity and accessibility. No mater of the way of travel researchers [11], [12], [13] consider that for the majority of people the acceptable travel time budget for commute is not much more than 30 minutes in a single direction and around 60 minutes for a working day. There are exceptions of course like people spending even 4 and more hours in daily commute using private cars or combination of different transport modes, including train for those living in settlements far from their work place.

Taking into account the average speed of transport modes is substantial in order to understand how far can reasonably be travelled by each mode and hence the likely nature of trips [14]. As stated before the average speed of travel is essential for choosing the way we move in regard with our travel time budget. Active travel modes of transport, and walking in particular, is much more limited in terms of distance. When assessing the reasonable duration of cycling commutes they can be compared in their average speed to public transport modes like city busses, trolleybuses and trams. In this sense, the speed will not be a barrier towards choosing bicycle for commute but mostly other factors like the existence and quality of infrastructure, safety, exertion, etc. They can easily change the attitudes of people for and against cycling in the city and be important factors that define the length of their trips.

There is no doubt that cities are as complicated as living organisms or even more and they function as the so called „whole systems“. Cities include areas with a variety of functions as part of our daily routine. And all of them, regardless of whether it is about places for living, relaxing and shopping or educational institutions, healthcare facilities and workplaces, including industrial sites with manufacturing and distribution, depend on the existence of a transportation network.

Register [4] draws our attention on the fact that „...the whole organism of the city we've been constructing for the last 150 years has been built on the basis of linking functions through ever lengthening strands of connection. First there were rails and trains and streetcars, then much more massively, highways, cars and trucks. ... But it does not have to be this way. Cities can be designed for pedestrians and bicyclists, taking up very small areas of land in more compact development. ... If one imagines today's typical metropolis of low density development and scattered higher density city centers linked by freeways it is possible to imagine a transition in which city centers, district centers and neighborhood centers are becoming much more "mixed use," as planners say, with more people moving closer to jobs and commerce in areas that can be served well by bicycles and transit.

4. ACTIVE COMMUTING IN PLANNING OUR SETTLEMENTS

4.1. The benefits, concerns and importance of active commute

Active commute is part of the active mobility and as such it has the same benefits but more closely connected and related to the business as it relates mainly to the working population. Many researchers like Pisoni et al [15] state that the benefits of active mobility are on multiple dimensions: i.e. on climate, health, jobs, air quality. When it comes to climate change, we must emphasize the role of active mobility in reducing CO_2 emissions, and from a health perspective, active mobility can help address the issue of increasing rates of overweight and obesity. By encouraging cycling in a city, one can also expect economic benefits in terms of job opportunities, and not only a better health, environment and quality of life [15].

Benefits can be found in improved physical and mental health, reduced traffic congestion, improved environmental sustainability, increased community connection, improved safety and finally in financial savings that come as an outcome of the above-mentioned.

The health benefits of active mobility are indisputable, and we can observe many of them by reducing physical inactivity and obesity. In our daily life, as stated in the previous part of this paper, most of the people spend around 60 minutes a day in commute. So if towns and cities can provide favorable environment for people to walk and bike more (or use some other active mobility means like skateboard, roller skates/inline skates, kick scooter, etc.) and easy connections to public transit a great part of the commute could be easily allocated to active mobility.

For example Raustorp and Koglin [16] conducted a study in Sweden, to see the effect of active mobility on reducing physical inactivity and obesity. For the needs of their research they used statistical survey and geographic analysis, based on data concerning the home and work addresses of the entire working population in the county of Scania, Sweden as of the end of 2014. This data set included a total of 575,959 individuals. The study showed that approximately 27.9% of the population can reach their workplace by a 15-min bicycle commute, while 47.2% can reach their workplace in 30 min. Raustorp and Koglin [16] claim that if all those living within cycling distance of work choose to commute by bicycle it would be possible to achieve a 47.2% modal share for active transport in Scania. Taking into consideration the WHO's world wide health advice of 30 min. of active mobility per day, a considerable amount of people could accomplish this target solely by commuting.

Regarding the possible switch from motorized personal travel to active mobility we can observe one main problem - most of the people are afraid to change their lifestyle. And the major concerns of people relate to lack of infrastructure, safety and time.

A key point, to facilitate the diffusion of bicycle and active mobility is, as expected, the need of good active mobility infrastructure (e.g. pedestrian streets or bike lanes) claims Pisoni [15]. Maltese et al [17] analyzed factors encouraging people to choose the active mode of travel for the city of Kaunas in Lithuania. They proved that one of the most important factors preventing people from choosing active modes of travel are distance and a lack of convenient infrastructure. The study showed that distance and time are in primary importance for car users to encourage walking. And traveling greater distance is normally associated with time loss or in other words spending more of our daily travel time budget. Regarding the infrastructure research participants put on first place the safety factor.

And as for cycling the study demonstrated that the most significant factor for car and public transport users was the wider cycling network and bicycle safety. Lack of safety, potential thefts, crash risk, long distances and topography, and a lack of proper infrastructure are described by Useche et al [18] as the most discouraging factors for using bicycles inside the city. According to them having a bike would encourage more public transport users to cycle, meanwhile, having more time would encourage more car users to ride their bicycles instead of drive their cars.

4.2. The case of Varna and a good practice from Spain

4.2.1. Varna – problems and opportunities

Varna is a seaside city and resort in eastern part of Bulgaria and with its 311 093 inhabitants [19] it is the third largest city after the capital Sofia and Plovdiv. Regarding the active mobility we can observe many problems, some related to pedestrian traffic and more related to the use of bicycle for transport.

As part of the work of Varna Free University (VFU) team for the Interreg project "CityWalk – Towards energy responsible places: establishing walkable cities in the Danube Region" the author of this paper took part in the preparation of "Strategy for the development of pedestrian traffic and active forms of mobility in the city of Varna" (2019) [20]. The goal of the Strategy was to establish the main directions of the policies of the Municipality of Varna towards developing urban environment, social and economic conditions and public attitudes stimulating active mobility forms and sustainable modes of transport, and on this basis also to offer guidance for initial actions implementing these policies. Assessing the current status of the active mobility in Varna the VFU team found that there are many issues that need to be solved in order to achieve safe, convenient and accessible urban environment. This should be a major goal in front of the local authority as the municipality of Varna, including the surrounding resorts, is attracting hundreds of thousands of tourists each and every year. And if we assume, however, that there have been some, albeit small and slow changes towards improving conditions for pedestrians and combined journeys with public transport during the last three years, this is definitely not the case when it comes to bicycle transport. The problems and failures related to the development of bicycle transport in Varna are mostly due to the lack of dedicated and comprehensive active mobility transportation plans, the reluctance of the local government to conduct such planning as it is not mandatory, and the poor planning and implementation of the partial plans that are made. This leads to safety issues and conflicts with pedestrians and motorized traffic. The bicycle network developed so far is insufficient and inappropriate for cyclists, as a form of urban mobility. Building bicycle lanes in Varna began in 2007-th with a 1,1 km. long track that connected the central part of the city with the Sea Garden. It was well implemented, but its current maintenance is poor. The next part of the bicycle network in Varna was built in 2015 with around 15 km. of new cycling infrastructure, poorly planned and built unfortunately, with the main idea to have longer network with smaller investments. The major issues associated with the bicycle-lane network are the safety, and the lack of connectivity and incompatibility with other traffic networks and modes of transport. At the moment, many of the bicycle lanes have neither a clear end nor a start. This makes it difficult for commuters to use a bicycle because lanes end unexpectedly and users have to choose alternative routes often with the risk of violating traffic regulations or risking their safety. Other problems are related to the lack of bicycle parking at appropriate locations and a bike rental system. Having such is important for Varna with regard to its resort status and the crowds of tourists visiting the city, but it has not been developed so far. Almost 8 years after the last bicycle lanes were built and more than 4 years from the adoption of the Strategy there are no new investments aimed to improve the current status.

The vision of the Strategy is with a time horizon the year 2030 and it states that “The city is the people”. The overall plan is Varna to become a city that is safer, more welcoming and more convenient for pedestrians and cyclists. The development of active forms of mobility should predominate in urban traffic and mobility and any resident should be able to access their job anywhere in the city within 45 minutes combining active mobility with public transport. Varna should become a city with a well-developed, fully integrated transport network complemented by an excellent infrastructure of pedestrian and bicycle routes that link the primary and all secondary service centers, including the expanded and improved central pedestrian zone and convenient access for pedestrians and cyclists to the Sea Garden. The Vision of this Strategy also includes convenient pedestrian and bicycle networks linking the southern and northern parts of the city, thus making Varna a leader in the development of pedestrian and bicycle networks on the Bulgarian Black Sea coast.

4.2.2. Bicivia: Connecting Territory on Two Wheels

According to a blog of Barcelona Metropolitan Area (AMB) dedicated to cycling [21], back in 1956 the Ministry of Public Works announced government intentions for the creation of new roads including bicycle tracks and tree-lined walks for pedestrians that will connect expanding cities with their metropolis and the rest of Spain. The plan began to be implemented and over the years kilometers of roads and motorways multiplied, but somehow the government completely forgot about pedestrians and cyclists.

60 years later, in 2016, the first Barcelona Metropolitan cycling network was presented and discussed with cycling stakeholders and in April 2016 the Metropolitan Council approved the Bicivia network.

Bicivia is a large scale project of Barcelona Metropolitan Area (AMB) that is focused on ensuring active mobility and connectivity across the 36 municipalities that are responsible for the design and construction of cycling networks on their territory. Planning cycling networks by their own municipalies fail to take into account the important social and economic flows linking them together. In the densely populated area of the AMB, this has resulted in low connectivity of cycling lines across the 36 municipalities. To solve this issue, one of the priorities in creating the Metropolitan Urban Mobility Plan and setting up the Mobility Council, was to interconnect the cycling network throughout the entire Barcelona Metropolitan Area [22]. The final plan foresees 550 km of connected cycling network that links urban centres and industrial and economic areas from all the 36 municipalities in the AMB. Today more than 50% of the primary and the secondary Bicivia network outside the city of Barcelona is a reality [23] and in 2025 at least the main network should be already built [22].

The online lexicon Urban Next [24] gives a clear description of the importance of Bicivia network for the links between municipality centers and the surrounding industrial areas. „As well as connecting municipalities and counties in the Metropolis Barcelona area, Bicivia also aims to improve the sustainable links between industrial estates and city centres. From a mobility perspective, municipalities possess a very diverse range of spaces that are often difficult to access in anything other than a motorised vehicle. Industrial estates – and their connections to central areas – are a good example, as evidenced by the links between Barcelona city centre and Zona Franca (the largest industrial estate in Catalonia).“ On 25 July 2017 a cycle path linking the two areas was opened, and pedestrians and cyclists are now able to travel safely from the heart of the city out to the industrial zone. The path runs for some 500 metres and allows its users to overcome the obstacles of the Ronda Litoral and the access roads to the Port of Barcelona, which were previously impassable for non-motorised traffic. The initiative is valuable for the sustainable connectivity with the city and Zona Franca, an area of great economic significance which is home to more than 250 companies. In 2005, 67% of its employees travelled to work by car, and AMB believes that the creation of cycle and pedestrian connection will make a significant contribution to changing the modal split.

4.3. Discussion

In the previous section we briefly introduced examples from Varna and Barcelona that are close related to the active mobility and active commute topic. The explored cities are very different in size and population, and are located in different regions of Europe, each with its own cultural, geographical, and historical characteristics. However, there are some similarities that are important regarding the subject of the current research:

- Both Varna and Barcelona are coastal cities, situated by the sea. This geographical similarity influences factors such as urban development, tourism, and recreational opportunities;
- Both cities attract a significant number of tourists;
- Both cities face challenges related to traffic congestion and air pollution, especially at the height of the tourist season.

Exploring how active mobility can help address these challenges is relevant to both cities.

Going back to the given examples we see hardly and partially developing active mobility services in the city of Varna with the efforts of NGO's and educational institutions to help the local government with their expertise and on the other hand the misunderstanding and even possibly unwillingness of the local government for long-term planning and investment in the development of a system for active mobility that will be valuable for all of the citizens.

On the opposite side we see the Barcelona Metropolitan Area with their huge plan for Bicivia Metropolitan cycling and pedestrian network (550 km) that connects and serves not only Barcelona residents but all the people of the 36 municipalities inside the Metropolitan Area.

The purpose of this paper was to provide an overview of the general aspects of active mobility, including the historical aspect of the topic and the opportunities for using the active mobility for commute and also presenting Varna's problems and the good example of Bicivia project. Prepared in this way, this short study will be the basis for a more in-depth analysis of the possibilities for carrying out active commute, considered in several aspects: the adjacent resort areas, the zones with educational function (kindergartens, schools and universities), the health care areas, the industrial areas, etc.

5. CONCLUSION

Active commuting, such as walking and cycling plays a crucial role in planning for connectivity of different functions inside the settlements including between living and industrial areas. Walking and cycling connections of different areas can provide affordable and sustainable transportation options, reduce traffic congestion, and improve air quality. In planning for connectivity, the focus should be on creating safe and accessible infrastructure for active commute. This includes investing in sidewalks, bike lanes, and public transportation systems that connect all the different functional areas of the cities. In addition, ensuring that public transportation options are affordable and efficient is crucial in encouraging active commuting.

Encouraging active commuting has the potential to not only improve individual health, but to reduce automobile dependency, and thus meet broader community objectives for a healthier, greener and safer environment. Active mobility definitely can contribute to a healthy and sustainable transportation system that connects urban and industrial areas. Connectivity between urban and residential areas with other functional zones is essential for the efficient functioning of towns and cities. Proper connections between these areas are necessary to ensure the timely transportation of people, goods and services, allowing for the smooth operation of businesses.

So we can conclude that if people want to have cleaner, more livable and connected settlements it is all about creating variety of functions in pedestrian and cycling proximity and well planned and implemented active mobility subsystem network.

REFERENCES

1. Kovachev Atanas, Slaev Alexandar, Nozharova Boriana, Nikolov Peter, Petrov, Plamen, 2018, Can public participation contribute to sustainable mobility? The experience of Bulgarian cities, in Bolay, J.C., Maričić T., Zeković, S. (Eds.), A Support to Urban Development Process, Belgrade: EPFL & IAUS, pp.59-79, ISBN: 978-2-8399-2394-1.
2. Oldenziel Ruth, Albert de la Bruheze, A.A.: "Contested Spaces: Bicycle Lanes in Urban Europe, 1900-1995." Transfers : Interdisciplinary Journal of Mobility Studies, Vol 1, No.2, 29-49, 2011. https://doi.org/10.3167/trans.2011.010203
3. Hannon Eric, McKerracher Colin, Orlandi Itamar, Ramkumar Surya: An integrated perspective on the future of mobility. Report produced by McKinsey & Company, Inc. and Bloomberg New Energy Finance. 2016. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/an%20integrated%20perspective%20on%20the%20future%20of%20mobility/an-integrated-perspective-on-the-future-of-mobility.pdf
4. https://www.resilience.org/stories/2006-09-12/cities-can-save-earth-urban-solution-climate-change-species-extinctions-and-peak/ (16.05.2023)
5. Nikolov Peter: Architectural ecology – Sustainable urban planning, In Proceedings of International Scientific Conference Architecture, Construction, Modernity, Varna, Bulgaria, 258-264, 31.05. – 01.06.2007.
6. Lindelöw David: Running to stand still - the role of travel time in transport planning. Urban move report. Urban insight 2018. SWECO. 2018. DOI: 10.13140/RG.2.2.35052.26247
7. Nikolov Peter, Nozharova Boryana: "The development of contemporary urban transportation in relation to urban street network", In Book of proceedings from 3rd International Conference on Urban Planning – ICUP 2020, Nis, 41-47, 12–13 November 2020. ISSN 2738-0548
8. https://www.bloomberg.com/news/features/2019-08-29/the-commuting-principle-that-shaped-urban-history (25.05.2023)
9. https://transportgeography.org (25.05.2023)
10. Nikolov Peter, "Timeline in urban form and transportation systems of some Bulgarian cities", In Proceedings of the 4th International Scientific Conference on Architecture and Civil Engineering ArCivE 2021. Varna, Bulgaria, 217-224, 2021. ISSN 2535-0781
11. Zahavi Jacov, Traveltime budgets and mobility in urban areas, U.S. Department of Transportation,Washington, D.C. 1974.
12. Stoichkov Asen, Komunikatsia i transport v naselenite mesta, DI „Tehnika", Sofia, 1980.
13. Marchetti Cesare, Anthropological Invariants in Travel Behavior, Technological Forecasting and Social Change, Vol 47, No.1, Elsevier Science Inc. 1994.
14. Abrantes Pedro, Ellerton Tom, Haines-Doran Tom, The Case for Active Travel. How walking and cycling can support more vibrant urban economies. Working paper. Urban Transport Group, Wellington House, Leeds, 2016.
15. Pisoni Enrico, Christidis Panayotis, Navajas Cawood Elena, Active mobility versus motorized transport? User choices and benefits for the society. Science of The Total Environment, Vol 806, Part 2, 2021, 150627, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.
16. Raustorp Johan, Koglin Till, The potential for active commuting by bicycle and its possible effects on public health. Journal of Transport & Health, Vol. 13, 72–77, 2019. ISSN 2214-1405, https://doi.org/10.1016/j.jth.2019.03.012.
17. Maltese Ila, Gatta Valerio, Marcucci Edoardo, Active travel in sustainable urban mobility plans. An Italian overview. Research in Transportation Business & Management, Vol.40, 2021, 100621, ISSN 2210-5395, https://doi.org/10.1016/j.rtbm.2021.100621.
18. Useche Sergio, Montoro Luis, Sanmartin Jaime, Alonso Francisco, Healthy but risky: A descriptive study on cyclists' encouraging and discouraging factors for using bicycles, habits and safety outcomes, Transportation Research Part F: Traffic Psychology and Behaviour, Vol. 62, 587–598, 2019. ISSN 1369-8478, https://doi.org/10.1016/j.trf.2019.02.014.
19. https://www.nsi.bg/en/content/2981/population-towns-and-sex (12.06.2023)
20. https://www.varna.bg/bg/162 (12.06.2023)
21. https://blogs.amb.cat/bicicleta/ca/2018/03/19/desplugues-a-barcelona-la-bicivia-7/ (11.06.2023)
22. https://medurbantools.com/wp-content/uploads/2020/10/Bicivia_-A-metropolitan-Bike-Lane-Network_FINAL.docx.pdf (11.06.2023)
23. https://www.amb.cat/en/web/mobilitat/projectes-oberts/detall//projecteobert/bicivia/6439486/11704 (11.06.2023)
24. https://urbannext.net/bicivia/ (11.06.2023)

AKTIVNA MOBILNOST KAO ALTERNATIVA ZA PUTOVANJE NA POSAO. PROBLEMI I MOGUĆNOSTI U GRADU VARNI

Postoji niz sinonima za opisivanje prevoza ljudi koji svoju fizičku aktivnost koriste samo za potrebe putovanja, a najčešće se koristi aktivna mobilnost. Meka mobilnost, mobilnost na ljudski pogon, aktivno putovanje, aktivni transport, aktivni prevoz i aktivno putovanje na posao su takođe na listi. I van svake sumnje najpopularniji oblici su hodanje i vožnja biciklom. Ovaj rad istražuje neke probleme aktivne mobilnosti, u vezi sa potrebom za održivim dnevnim putovanjem na posao. U ovoj tački postojanje održivih alternativa privatnom motorizovanom transportu je od vitalnog značaja za razvoj naselja, ali se često potcenjuje važnost meke mobilnosti u njihovoj povezanosti sa industrijskim područjima. Korišćenje aktivnih oblika transporta, uglavnom biciklističkog i pešačkog saobraćaja, kao i njihove kombinacije i javnog prevoza, šansa je da se urbani prostori učine pogodnijim za život. Mnogim oblastima je teško pristupiti bez ličnog motornog prevoza, a za grad Varnu susedna odmarališta i industrijske teritorije su tako upečatljiv primer jer je njihova veza sa ostatkom naselja puna prepreka za vožnju biciklom i pešačenje. U ovom radu, u okviru svoje teme, autor istražuje neke probleme sa kojima se ljudi svakodnevno suočavaju u gradu Varni i traži mogućnosti za buduća poboljšanja na osnovu primera dobre prakse iz Barselone.

Ključne reči: *aktivna mobilnost, svakodnevno putovanje na posao, industrijska područja, saobraćajne veze, održivost.*

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Original Scientific Paper

ASSESSMENT OF CIRCULARITY POTENTIAL IN FAÇADES OF HIGH-RISE BUILDINGS IN BELGRADE

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Abstract. *A growing trend in the construction of high-rise buildings is currently prevalent in Belgrade, where more high-rise buildings have been built in the last decade than in the previous 50 years. However, these buildings have a significant negative impact on the environment, as their sophisticated construction technologies demand substantial resources and energy consumption. The aim of this research is to assess the possibility of reducing the resource consumption of these buildings, focusing on the circularity potential of their façades. The research is conducted on typical façades of high-rise buildings in Belgrade. The applied methodology for assessing the circular potential of façades relies on numerical calculations of material circularity indicators and CO_2 emissions. Research findings draw conclusions about the circular potential at the beginning and end of the façade's lifecycle, covering the production, dismantling and disposal phases of integrated components. The study highlights differences in resource consumption based on the architectural characteristics of the examined façades and provides insights for their improvement through the implementation of materials with higher circularity potential and optimized impacts on the environment.*

Key words: *circular economy, material circularity indicator, recycle, reuse, end of life of buildings, CO_2 emission*

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1. INTRODUCTION

1.1. Background on high-rise buildings construction in Europe and Belgrade

The construction of tall buildings in Europe began in the 1950s, half a century later than in the United States. The delay in incorporating of this typology in European cities is primarily due to fears regarding its potential negative influence on the rich architectural heritage of the region [1]. Tall buildings in Europe are carefully adapted to the unique historical and urban fabric, which limited their height and the total number of buildings built [2]. Unlike tall buildings in America, which were characterised by uniformity of architectural expression, European high-rise buildings show a greater variety of forms and facades since there was a tendency to ensure that tall buildings harmonize with their surroundings [3].

Analysing the construction of high-rise buildings based on numerical data available in the Council of Tall Buildings and Urban Habitat database reveals that from 1971 to 1980, over 300 tall buildings were constructed, with a maximum height of 200 meters. In the following decade, there was a sharp decline in the number of constructed buildings followed by the slight increase by 2000. From 2001 to 2010, the construction of high-rise buildings tripled compared to the previous decade. From 2010 to 2020, a record number of high-rise buildings were built, over 700. Approximately 200 high-rise buildings have been constructed in Europe in recent years (Figure 1).

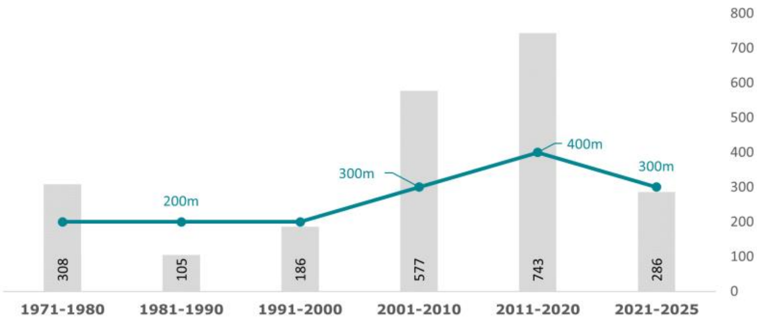

Fig. 1 The construction of high-rise buildings in Europe according to the period of construction and the maximum height achieved

The trend of building more high-rise buildings, which has been present in Europe since 2010, has also been observed in Serbia in the past decade. In recent years, more high-rise buildings have been built in Belgrade, the capital of Serbia, than in the previous 40 to 50 years. Although the first high-rise building in Belgrade was built in 1939. their construction in larger numbers began after the World War II [4,5]. In the second half of the 20th century, numerous residential neighbourhoods were formed on the outskirts of the city, which included residential towers. In addition to residential buildings, in the 1960s the construction of commercial high-rises in the city centre began. During that period, some of the city's main urban landmarks were built, such as Usce Tower 1 (1967, 141m), “Belgrade” Palace (1974, 101m), East Gate of Belgrade (1976, 85m) and Genex Towers or the West Gate of Belgrade (1980, 118m) as shown in Figure 2. After this period until 2020, there was no significant construction of high-rise buildings in Belgrade, despite numerous proposed projects in architectural competitions at the end of the 20th and beginning of the 21st century. However, in recent years, several high-rise buildings have been built and even more are planned for the coming years. In recent years, Ušće Tower 2 (140 m), Skyline Tower (130 m), West Tower 65 (155 m) and Belgrade Tower, currently the tallest building in the city at 168 meters, have been built in Belgrade (Figure 2).

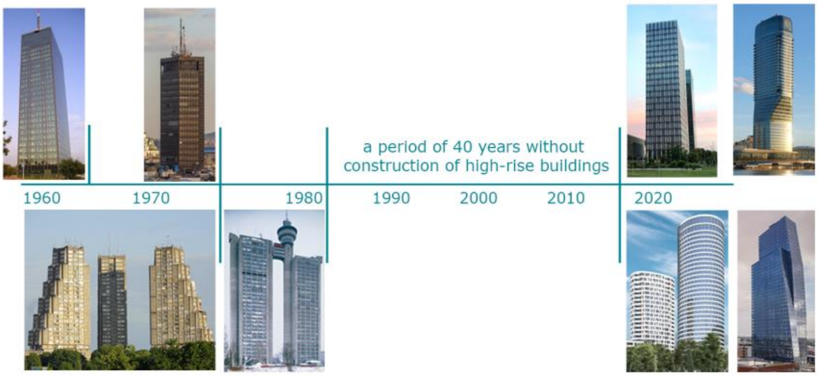

Fig. 2 High-rise buildings in Belgrade

This sudden increase in the construction of high-rise buildings raises concerns due to the absence of planning documents in Serbia providing guidelines for their design. The only document that addressed the typology of high-rise buildings in Belgrade was the High-Rise Buildings Study, conducted by the Belgrade Urban Planning Institute in 2011. However, since the study was abolished in 2014, no new regulatory documents related to it have been published. Some of the study's most significant conclusions emphasized the need to consider the impacts of high-rise buildings on Belgrade's existing historical and urban environment [4]. Within the study, four zones for the construction of buildings ranging from 26 to 150 meters high were proposed. It suggested constructing buildings taller than 100 meters exclusively in New Belgrade, while in the old town, only buildings up to 50 meters were contemplated to prevent adverse effects on the rich cultural heritage of this area of the city. An overview of the proposed construction zones indicates that during the positioning of most high-rise buildings built in previous years in Belgrade, the recommendations outlined in the study were not considered.

High-rise buildings in Belgrade were also not designed in accordance with the principles of energy efficiency, resulting in significant negative environmental impacts due to excessive resource and energy consumption, which is particularly notable considering their facade systems. The integration of sustainability concept into high-rise facade design has notably altered their aesthetic features [6,7]. Facades have the most significant influence on energy performance of high-rise buildings [8,9]. Nevertheless, the optimization of facade systems and materials to minimize operational energy consumption frequently leads to an increase in the embodied energy of the facade system

[10]. Although structural elements constitute the largest share of a building's embodied energy, facade envelopes, accounting for up to 30% of the total, rank second [11]. However, unlike structural components, facade system elements typically have shorter lifespans, necessitating increased maintenance and repairs, resulting in comparatively higher energy consumption and CO_2 emissions throughout the building's lifecycle [12]. While many studies focus on reducing carbon emissions in tall buildings by addressing structural systems [13,14,15], fewer concentrate on optimizing facade envelopes. The intricate nature and stringent standards of facade envelopes pose challenges in optimizing material quantity, resource consumption and energy use [16,17].

It can be concluded that the facades of high-rise buildings pose a unique challenge in terms of optimisation regarding circular potential. They have a lifespan of 25 to 30 years, requiring multiple replacements over the building's lifetime and have crucial role in the energy performance of buildings, demanding complex systems comprised of various elements and materials.

1.2. Circular economy in construction sector and façade industry

Construction industry is one of the biggest polluters in terms of carbon dioxide emissions and it is responsible for the consumption of 35-45% of natural resources and 25-40% of global energy [18,19]. Currently, the construction sector operates under a linear economy model, which is based on unrestricted exploitation of natural resources during the construction and use phase of buildings. Furthermore, a significant issue arises during the demolition phase, leading to generation of substantial waste deposited in landfills. To mitigate the adverse effects of this model on the environment, there is a growing interest towards transitioning to a circular economy. The goal of a circular economy is to enable the continuous circulation of resources which requires the implementation of various strategies to facilitate the reuse of materials at the end of a building's lifecycle [20,21,22]. In this manner, waste is reduced by reintegrating previously used materials back into the production process, thereby avoiding the need for repeated extraction of natural resources and saving energy required for these processes. Circular economy entails strategies of renewal, repair, reuse, or recycling aimed at extending the lifespan of each material, with a focus on using energy derived from renewable sources in these processes [23,24]. In addition to resource circulation, extending the lifecycles of products and materials is significant for circular economy. Therefore, extra attention is given to the maintenance and servicing of products to prolong their lifespan [24].

The European Green Deal and the EC Action Plan for the Circular Economy require EU member states to develop documents initiating the transition to circular economy [25] and many national strategies were published between 2016 and 2021 [26,27]. Serbia published its first national strategic document addressing the concept of circular economy - the 'Roadmap for Circular Economy in Serbia' in 2020. It includes guidelines for the development of individual economic sectors, including the construction industry [28].

During construction and throughout the use phase, buildings consume a large amount of natural resources and energy. An additional problem arises at the end of their lifecycle, during demolition, resulting in a significant amount of waste disposed of in landfills, further harming the environment [29]. Circular economy emphasizes the importance of tracking embedded materials from production to dismantling or demolition phases of buildings. It proposes a new approach to resource use, striving for conservation through reuse, repair, and recycling of construction components or materials. Circular economy aims to eliminate construction waste through strategies enabling once-installed products to return to the production process, thus reducing waste at the end of buildings' lifecycle. Despite legal requirements for proper collection, classification, and disposal, most of the construction waste in Serbia ends up in landfills. Reports suggest that the construction waste constitutes two-thirds of total waste in Serbia, with only 5% being recycled, a significantly lower percentage compared to other European countries. It can be concluded that the application of the circular economy concept in construction in Serbia would be significant for reducing the waste generated from buildings.

Although circular economy focuses on resource reuse at the end of the lifecycle, its realization depends on adequate design at the beginning of the lifecycle. During the lifespan of a building's structural system, its facade and interior organization must change several times [30]. Following current energy efficiency standards regarding thermal and visual comfort, facade components are often replaced to achieve better insulation or regulate shading and lighting levels. Given the high standards that facades of high-rise buildings must meet, they are not as flexible as other building systems to easily align with the circular economy concept, presenting numerous challenges for their optimization. Facades are complex structures that must meet various requirements and are influenced by different engineering disciplines, production chains, and value systems [12].

Considering the unitised curtain walls used in facades of high-rise buildings it can be concluded that their manufacturing process is already in line with circular economy concept, since it incorporates prefabrication which includes optimised production [31,32]. A bigger problem in the optimization of these facades refers to the standardly applied materials, as well as their uneven lifespan, which often leads to replacement of the entire facade because of the one element. Considering the lifecycle within curtain walls, a significant difference is observed between individual components because aluminium frames have a lifespan of 50 years, insulated glass units 25 to 30 years, and seals only 15 to 20 years [31,33]. It can be concluded that during the lifespan of an aluminium frame, other components such as glass must be replaced at least once, while gaskets and seals are replaced twice. These differences leave ample room for optimization in line with the principles of the circular economy.

Considering the complexity of facade systems and the number of different materials they consist of, their production is associated with the consumption of a large amount of non-renewable resources and a significant amount of waste generated on-site during their dismantling or demolition. The long-term performance of facade systems depends on the quality of the materials they are made of, as well as the connections of many components that cannot be easily dismantled and adapted during their lifecycle, which poses one of the biggest challenges for their alignment with the circular economy [34,35]. In most studies, it is assumed that the greatest potential for optimizing facade systems in the circular economy lies in designing for disassembly, aligning the lifecycle of installed elements, using materials whose production process involves a higher proportion of secondary raw materials, as well as optimizing the reuse and recycling of materials and components at the end of the facade system's lifecycle.

The generally low rate of use of recycled resources in the Serbian construction industry poses one of the major obstacles to transitioning to a circular economy. This refers particularly to materials such are aluminium and glass which are commonly used in facades of high-rise buildings in Serbia. In order to improve the circularity potential of facades of high-rise buildings in Belgrade strategies that involve material optimisation are applied in the presented research. This refers to the use of materials with a higher proportion of secondary materials, materials that can be reused at the end of the lifecycle, and those whose production and disposal have fewer negative environmental impacts.

2. METHODOLOGY

For an assessment of the circularity potential of facades of high-rise buildings in Belgrade and possibilities for their improvement, a methodology which includes following steps has been outlined:

1. Analysis of contemporary façades of high-rise buildings in Belgrade constructed during the previous decade.
2. Definition of reference (base) models of façades based on analyses of façade systems and applied materials in high-rise buildings in Belgrade to numerically assess their circularity potential in relation to specific architectural characteristics.
3. Analysis of typical components and materials in defined facades corresponding to the current façade industry developments in Serbia, through contact with manufacturers and contractors.
4. Collection of Environmental Product declarations from manufacturers and obtaining of data for numerical calculation referring to characteristics of applied materials, their production processes and possibilities for their reuse.
5. Defining methods for assessing circularity potential referring to material flow analysis, calculation of circularity indicators for production and end-of-life phase and CO_2 emission through the whole life cycle of defined facades.
6. Research of possibilities for improvement of base façade models through the application of materials manufactured using a higher amount of recycled feedstock characterised by lower CO_2 emission during their life cycle.
7. Calculation of circularity indicators and emission of improved models and comparative analysis with basic models.
8. Evaluation of achieved improvements depending on façade models and determining the possibility of reduction of CO_2 for a façade lifespan of 50 years.
9. Discussion of results and drawing conclusions about the possibilities of optimizing resource consumption and reducing negative environmental impacts of façades of high-rise buildings depending on architectural concept and implementation of materials with higher circular potential.

2.1. Data collection

The gathering of data for numerical calculations and assessment of circularity potential of facades was conducted through the research of façade industry in Serbia and Europe and contact with the manufacturers of unitised curtain walls and their components. The first step of the research included the analysis of systems and materials typically used in the facades of high-rise buildings in Belgrade. Data about facade components and materials regarding the manufacturing process, resource consumption, end-of-life treatment, and greenhouse gas emissions were collected. The second part of the research focused on exploring possibilities for improving the circularity potential of standard materials. This included an analysis of the current application of the circular economy in facade products available on the European market and advancements in their development.

Environmental product declarations were collected from manufacturers in Serbia and Europe in order to obtain specific data for each component of the facade. Environmental Product Declarations (EPDs) use the life cycle assessment method to quantify and communicate the environmental impacts of products or assemblies throughout their entire life cycle. The standard specifies information that every EPD must contain:

- General product information, manufacturer details, applied standards for life cycle assessment, verification system information and declaration expiry date.
- Detailed product information, its use, technical standards fulfilled and necessary resources for production.
- Product life cycle assessment data, system boundaries or covered modules of the conducted LCA method, estimation and data assumption of phases where calculation was not possible due to lacking cycle data, detailed material quantities comprising the product.

The main part of the declaration is a tabular representation of all individual environmental impact indicators divided across all life cycle stages. Basic rules for EPDs in the construction sector are defined by the standard EN 15804. Current EN 15804+A2 standard requires the assessment of 13 core environmental impact indicators.

Environmental Product Declarations in the construction industry are published on various international online platforms by organizations verified for their approval. There is no central database including all construction products, nor is there a national database for Serbia. Numerous product declarations for curtain wall systems are available in international databases, but their application has significant limitations and often leads to inaccurate results. Data on the environmental impacts of a specific curtain wall system are mostly expressed through numerical values for a functional unit of 1 m² of facade area. The limitation of such calculations lies in their coverage of only a small area of the facade without considering its entire dimensions or specific architectural characteristics of the whole facade. Also, generic data on glass panels and gaskets are often assumed within the declarations, while opaque panels are not considered.

It is a mistaken assumption that module D can be taken as a relevant indicator of circular economy in facade system declarations. Namely, the results within this module depend on the chosen inventory for the declaration and its production phases. If more primary resources are used in the production phase that can otherwise be recycled at the end of the life cycle, the results in phase D are more favourable. On the other hand, if more secondary resources are used in the production phase, the potential for their recycling is already optimized, resulting in lower phase D results.

Based on these limitations, it is concluded that the use of generic declarations for facade systems will not give accurate calculation results for the assessment of circularity potential, which is why declarations of individual façade components are used in this research.

2.2. Circularity indicator

One of the challenges in applying the principles of the circular economy in the process of architectural design is the difficulty of their evaluation. There is no standardized metric system that can be used to quantify the effectiveness of implementing circular economy strategies during the design phase. In recent years many researchers addressed this problem and proposed various methodologies for qualitative or numerical assessment of the circular potential of buildings. Consequently, diverse indicators have been formulated, encompassing aspects such as material circularity, disassembly, reusability, durability, and life cycle assessment methods [36,37,38]. The complexity of buildings emerges as the key challenge in assessing building circularity, given their composition of numerous different systems and interrelated components. This challenge is further compounded by the differing lifespans of components and their variable environmental impacts.

One of the initial indicators for assessing the circular potential of individual materials and products was developed by the Ellen MacArthur Foundation [39]. For several years this method was used as the primary calculation tool for determining numerical values of product circularity. However, this indicator is of a general nature and is not specified for construction industry, indicating its limitations when applied to building assessments. A significant disadvantage of this calculation method is the inability to distinguish between materials recycled during the production of components in the factory and those obtained by recycling previously used components.

The challenges of assessing the circularity of buildings include an extremely complicated and time-consuming process of collecting data based on current research and availability. Due to these challenges, numerous tools and software plugins have been published in recent years to facilitate the measurement of the circularity potential of buildings.

One of those is the *Madaster Platform* which is used in several European countries as the most reliable software for the comprehensive assessment of circularity potential of buildings and their components. It encompasses the evaluation of material flows, an adapted version of the material circularity indicator specifically for buildings, a disassembly index and a life cycle assessment [40]. Due to its capability to calculate multiple indicators based on a single input of data, it was chosen for the numerical computations conducted within this research.

The Madaster Circularity Indicator (MCI) is used to assess the circularity potential of a building and is calculated numerically for each phase of its lifecycle: construction, use, and end-of-life [41]. To perform the calculation, the platform user must input detailed data about every individual material or product comprising the building, either through a BIM model or an Excel spreadsheet. This initial data entry is followed by providing detailed information about the material's origin, lifespan and end-of-life treatment [42].

In the construction phase, the ratio between primary and secondary raw materials used in manufacturing all parts of the building significantly influences the indicator calculation. During the use phase, the lifespan of installed products is assessed in relation to the average functional lifespan of similar products on the market. In the demolition phase, or end-of-life of the building, the circularity indicator is predominantly influenced by the quantity of materials or products that can be reused or returned to the production process in some way, thereby avoiding waste.

Based on the entered data, several values of the circularity indicator are obtained, including individual indicators for each product or component, indicators for each lifecycle phase of the entire building, and the overall indicator for the entire building lifespan, considering all previously mentioned factors.

The circular economy indicator calculation is based on determining a value that deviates from the standard linear economy flow and is calculated according to the following equation:

$$CI = 1 - LFI \ x \ F(X)$$

where CI represents the circularity indicator, LFI the linear economy flow and F(X) represents the utility factor of the product (expressed in years).

For a calculation according to the presented equation, it is necessary to first establish the linear economy flow, which requires consideration of multiple factors according to the following equation:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$$

in which V stands for the quantity of primary raw materials used for manufacturing of products. The same materials then determine the value of W, which relates to the amount of waste generated in the demolition phase of products. The fraction of primary raw materials is calculated according to the equation:

$$V = M\,(1 - F_R - F_U - F_S)$$

where M represents the product mass (kg), and the other factors represent the percentage share of raw material origin. F_R refers to the share of the product's mass made using recycled materials, while F_U represents the share of the product's mass made from reused materials, and F_S represents the share of organic material.

The amount of unrecoverable waste W (kg) is calculated according to the following equation:

$$W = W_0 + \frac{W_F + W_C}{2}$$

Which is based on additional calculations of the quantity of non-recoverable waste disposed on the landfill – W_O, waste generated during further product recycling processes - W_C, and waste generated when producing recycled feedstock for a next product - W_F.

The calculation of the amount of waste disposed of in landfills is calculated according to the equation:

$$W_0 = M\,(1 - C_R - C_U)$$

based on the product mass - M, the share of material collected and returned to the production process through recycling - C_R and the share of material collected and directly reused - C_U.

The quantity of waste generated during material recycling processes is calculated based on the equation:

$$W_F = \mathrm{M}\,\frac{(1 - E_F)\,F_R}{E_F}$$

where M represents the material mass in kg, E_F denotes the recycling process efficiency, and F_R represents the share of materials that will be usable as recycled feedstock in the next lifecycle.

In the case of the recycling process, a certain amount of waste is generated depending on its efficiency, calculated according to the equation:

$$W_C = M\,(1 - E_C)\,x\,C_R$$

for which data on the material mass - M, recycling process efficiency - E_C, and the share of materials collected and returned to the production process through recycling - C_R must be specified.

After calculating the linear economy flow, to determine the circularity indicator according to the first equation, it is necessary to calculate the F(X) factor, which relates to the number of years of functional use of the product, or the expected lifespan of the product within the building. This is calculated using the equation:

$$F(X) = \frac{0{,}9}{X}$$

Where X is calculated using the equation:

$$X = \frac{L}{L_{av}}$$

based on the average lifetime of the product L and the lifespan of similar products based on the industry average - L_{AV}.

The previously shown equations are used to calculate individual materials incorporated into building components. However, building complexity rarely involves the components composed of only one material. Therefore, after conducting the previous calculations for individual indicators of each material, the cumulative sum of components is determined.

The cumulative result for the linear economy flow of all materials within installed components is then calculated based on the previous calculation according to the following equation:

$$LFI = \frac{V + W}{2M + \sum_X \frac{W_{F(X)} - W_{C(X)}}{2}}$$

The material circularity indicator defined by the Ellen MacArthur Foundation is quantified on a scale from 0 to 1. In this context, 0 signifies the flow of a completely linear economic model, whereas 1 signifies a fully circular model. On the Madaster platform, this indicator is further refined into a percentage format, spanning from 0 to 100%, to present the circularity potential across production use and end of life phases of the life cycle. The overall Madaster circularity indicator does not rely solely on an aggregate of the three life cycle phases. Instead, it is notably influenced by computations pertaining to both construction and demolition phases, as per the previously outlined equations. Data corresponding to each mathematical value in equations is inputted into the software. The final outcome is not presented as a detailed numerical calculation but rather as a graphical representation.

The interpretation of the circularity indicator's percentage outcome classifies the building ranging from a linear flow (0%) to full alignment with circular economy (100%). A building with a short life span whose components are constructed predominantly using primary raw materials, which is characterized by a shortened lifespan and culminates in a significant deposition of material in landfills after demolition, is considered a linear structure with a nominal circularity indicator in the range of 0 that is 10%. In contrast, a building constructed entirely of recycled or reused materials and products, which can be reused in the future, is classified as a 'circular' building, with a maximum circular potential score of 100%. This holds even if its functional life cycle is shorter than average. In practical terms, buildings have scores varying between 0 and 100% due to the inevitable mix of primary and secondary resources used in their components, different lifespans and the potential for partial reuse before some materials end up as waste at the end of their life cycle.

2.3. Assessment of CO_2 emission

The calculation of CO_2 emission is based on the methodology of Life Cycle Assessment (LCA). It represents the most widespread method for determining the environmental impact assessment of a specific product. The method entails a comprehensive analysis of impacts throughout the entire life cycle, encompassing processes from raw material extraction from the natural environment, material and component production, transportation, installation, use, maintenance, to the final stage of disposal or recycling [43]. The use of LCA has become widely adopted in the construction industry over the last decade and is utilized for assessing individual materials or building assemblies [18].

The methodological process in this research involves several steps: defining the applied products and materials incorporated into the façade, obtaining data on their environmental impacts, calculating $C0_2$ relative to quantities and material data and analysis of obtained results. The life cycle assessment comprises phases A (production and installation), B (use) and C (demolition), along with phase D, which provides additional information on end-of-life possibilities.

$C0_2$ emission is calculated based on the data from EPDs regarding Global Warming Potential (GWP tot). This refers to the total global warming potential obtained as the cumulative result of 3 indicators (fossil-GWP f, biogenic-GWP b, and land use GWP-luc). Global warming is a phenomenon related to the increase in the Earth's average surface temperature, primarily due to the rising levels of greenhouse gas emissions, with carbon dioxide being particularly prominent.

CO_2 emission is calculated over a 50-year period, representing the minimum duration of use for high-rise buildings with the same spatial function that do not require changes in the facade layout. Within this timeframe, one replacement of the façade or two life cycles of all components within the segment are anticipated. Data concerning CO_2 emission during the production, use and end-of-life phases are sourced from the environmental product declarations of individual components obtained from the manufacturers.

3. Models of Facades of High-rise Buildings in Belgrade

3.1. Façade systems and materials of high-rise buildings in Belgrade

The predominant facade system used in contemporary high-rise buildings in Belgrade is the unitized curtain wall system. This system entails dividing the facade into elements assembled in factories before installation, which greatly facilitates the installation of facade systems at considerable heights. These facade elements are installed on-site as finished panels and can adopt various shapes based on the building's geometry or the desired architectural concept of the building envelope.

Observing the buildings built in recent years in Belgrade, it can be concluded that two basic concepts are equally present in the architectural design of the facades of high-rise buildings:

- Fully glazed facades that do not imply a visual difference between transparent and opaque elements. This concept is the most common choice when the architectural concept aims to create a unified volume to emphasize the building form as in West 65 (Figure 3a).

- Facades aiming to achieve a more dynamic visual effect through combination of transparent and opaque elements. In these facades the most prevalent concept in architectural practice is the application of opaque panels at the level of ceilings as in the facades of Skyline commercial building and Belgrade Tower (Fig. 3b and 3e). In recent years, visual dynamism of facades has been achieved through combinations of transparent and opaque panels organized in irregular vertical and horizontal grids as in Usce Tower 2 and Skyline residential building (Fig. 3c and 3d). Additionally, more dynamic effects on large glass surfaces of the facades could be achieved through the implementation of elements of different sizes, as in the Belgrade Tower (Figure 3e).

Fig. 3 Facades of high-rise buildings in Belgrade: a) West 65, b) Skyline - commercial building, c) Usce Tower 2, d) Skyline – residential building, e) Belgrade Tower

The most commonly used façade system in high-rise buildings in Belgrade is the unitized curtain wall with cover caps. These façade systems include following components: an internal aluminium frame composed of horizontal and vertical profiles, an external aluminium profile or cover caps, double-glazed units in vision panels with low-e coatings, double-glazed units in opaque panels, thermal insulation at the ceiling level, gaskets and thermal breaks.

In order to determine the specific characteristics of these façade systems of high-rise buildings in Belgrade, technical documentation was collected from façade planners, manufacturers and contractors who were involved in their construction. Based on the analysis results, basic façade models have been defined, which will be the subject of further research. These models represent typical examples of the prevalent façade types found in high-rise buildings in Belgrade. The objective is to determine their circular potential in relation to architectural characteristics of the facades. The analysis encompassed the dimensional aspects of façade elements, main components of the façade system and applied materials.

3.2. Definition of base façade models for numerical assessment

Based on the previous analysis 6 base models have been defined representing the most common architectural concepts applied facades in high-rise buildings in Belgrade. These models are used for numerical assessment of circularity potential. All models are calculated for a façade segment of the same dimensions, measuring 15 meters in width and 12 meters in height. This was determined based on its adaptability to various structural systems, considering the typical column grid and floor height of 4 meters. Therefore the height of the façade elements in all models is uniform, measuring 4 m. Vertically, the elements are divided into two sections: the upper one measuring 3m in height and the lower one measuring 1m and aligning with the ceiling level.

Depending on the architectural characteristics of each model, the width of the basic façade elements ranges from 1.25 meters to 1.5 meters, reflecting the common dimensions found in high-rise buildings in Belgrade. Furthermore, depending on these architectural characteristics, models may incorporate additional divisions of elements, window openings, and varying ratios of transparent and opaque façade areas. The defined base models are:

- Model 1 features a fully glazed façade without visual distinction between elements, similar to the design of the West 65 building. The façade segment consists of 36 basic elements measuring 1.25x4 meters. Vision panels with a height of 3 m are designed with laminated glass and a low-e coating, while opaque panels with a height of 1 m feature tempered glass.
- Model 2 consists of 30 elements measuring 1.5x4 meters. It assumes the same vision panel configuration as the previous model but incorporates spandrel panels with an aluminium finish in the opaque sections at the ceiling level. This type of façade is encountered in buildings Skyline, Usce Tower 2 and Belgrade Tower.
- Model 3 shares the characteristics of Model 1 but includes additional 8 window openings, each 2 meters in height. The glazing units remain the same as the ones in Model 1. This model is based on the façade design of the West 65 building.
- Model 4 represents a façade consisting of 30 basic elements with dimensions of 1.5x4 m. It introduces additional divisions of basic elements and vertical opaque panels to create a more dynamic façade, resembling that of the Usce Tower 2 building. The basic elements are divided into two sections: the first, 1.1 meters wide, relates to the vision panel, while the second, 0.4 meters wide, forms the vertical opaque panel.
- Model 5 also assumes 30 basic elements each 1.5 meters wide, which are occasionally further divided into two sections (each 0.75 meters wide), following a dynamic elements division similar to the one found in the Belgrade Tower.
- Model 6 is based on the façade of the Skyline building and assumes equal ratio of transparent and opaque surfaces. It consists of a total of 36 elements (1.25x4m), with half designated as vision panels with glazing units and the other half as opaque surfaces with aluminium spandrel panels.

Configuration of façade segments of base models 1-6 is shown in Figure 4.

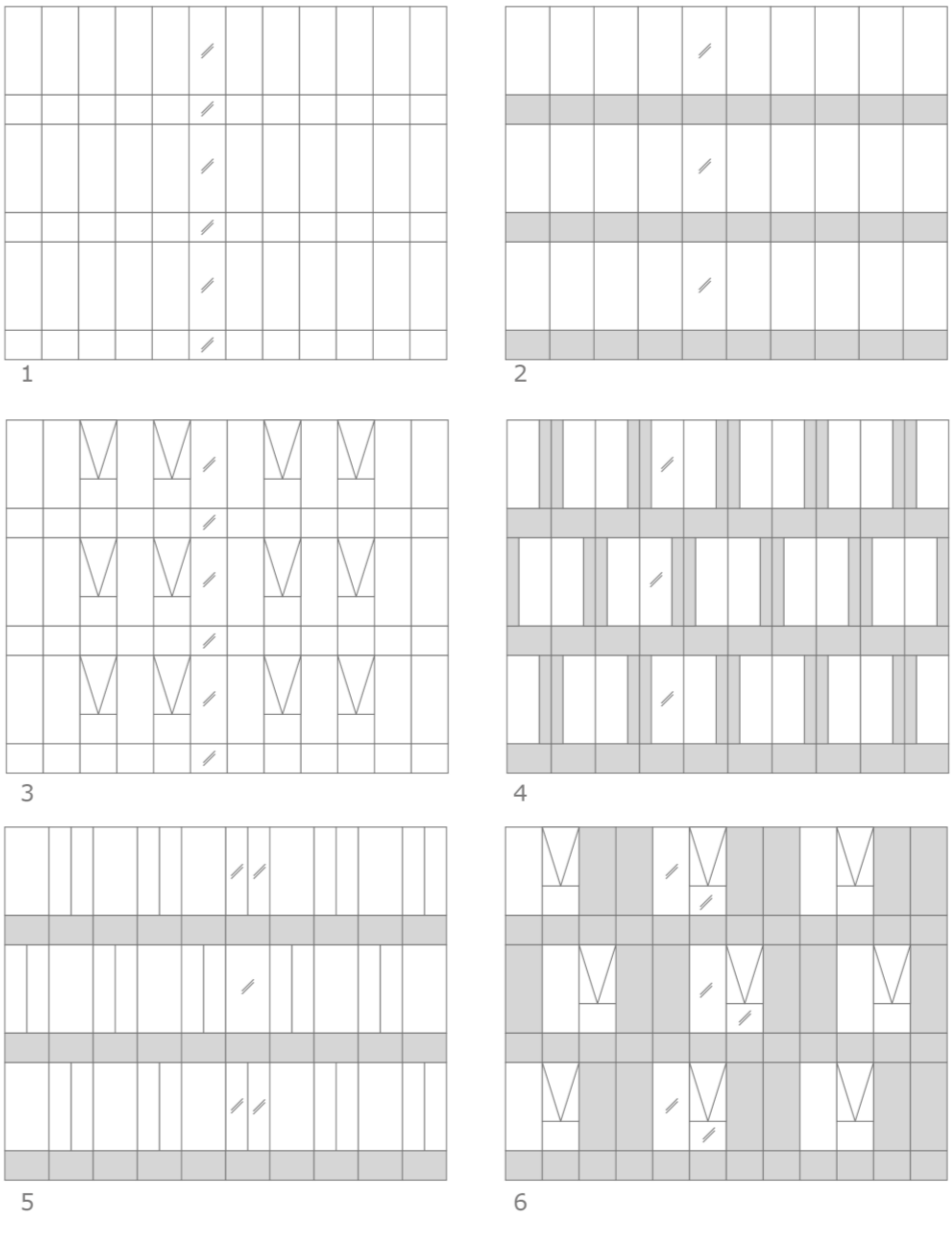

Fig. 4 Defined base models of façade segments for numerical assessment of circularity potential

3.3. Inventory for numerical assessments

Based on the collected EPDs for façade components of base models the inventory for numerical calculation has been defined. Considering the architectural characteristics of the defined base models, the following inventory for calculating circularity indicators and CO_2 emissions was used:

- For aluminium frame profiles, data relating to the current European average production of anodized aluminium profiles from the EPEA database available within the Madaster platform are used. The share of recycled feedstock in the production phase of these profiles is 40%. Although this represents an exceptionally low proportion of recycled material, it aligns with the current industry average in Serbia. It is assumed that approximately 96% of the initially installed material is collected at the end of the life cycle for possible reuse. However, a certain amount of material is lost in this process, as recycling efficiency is limited to 95% (an estimation used in declarations of all aluminium profiles available on the market). The mass of material in façade segments is calculated considering that the weight of aluminium is 2700 kg/m^3.
- In vision panels a double-glazed units (DGU) are used, consisting of an outer layer of laminated glass comprised of 2 layers of flat glass with a low-e coating and single inner flat glass layer with total unit thickness of 36.76mm (50.8 kg/m^2). In non-transparent panels at the ceiling level, a DGU with outer layer of tempered glass is foreseen with low-e coating and inner glass layer with total unit thickness of 30mm (35 kg/m^2)
- The EPDs for DGUs include all life cycle phases of flat glass, lamination processes, coatings, as well as the assembly of the glass package. The production of these units does not include recycled material and it is assumed that the whole components will be disposed in landfills at the end-of-life cycle in façade segments.
- Opaque panels contain mineral wool as thermal insulation (15mm) where 98% of the material is comprised of primary feedstock, according to manufacturer declarations for production of this component in Serbia. At the end of the life cycle, only 2% is recycled, resulting in significant material loss. As the final cover an aluminium spandrel panel of 4mm is assumed. A EPD of component used in the Usce Tower 2 is used as inventory. It is characterized by 40% recycled materials used in manufacturing, with 95% available for recycling at the end of the life cycle. Due to material loss during the recycling process, 91% recycled aluminium is available at the end, and the insulation panel core is entirely disposed of in landfills. The quantity of material within the panels is calculated based on a weight of 7.90 kg/m^2.
- The data from Ökobaudat database (also available in the Madaster platform) is used as inventory for calculation of gaskets and thermal breaks.

4. RESULTS

4.1. Material Flow Analysis

The first step in the assessment of circularity indicator is the calculation of embedded materials for façade segment for each of the base models. The quantities of installed materials are calculated based on technical specifications and details of the unitised curtain wall façade system obtained from manufacturers, the configuration of insulated glass units and technical documentation of individual products. For all models the calculations are conducted for a façade segment 15m wide and 12m high. The calculation includes following components for all models:

- Internal aluminium frame profiles and external cover caps;
- Double glazed units with laminated glass in vision panels;
- Thermal insulation in opaque panels;
- Gaskets and thermal breaks.

According to the different architectural characteristics of the basic models, the following components are additionally calculated depending on the model:

- Double glazed units with tempered glass in spandrel panels (models 1 and 3);
- Window aluminium frame and additional gaskets (models 3 and 6);
- Spandrel panels (models 2, 4, 5, and 6);
- Thermal insulation, aluminium profiles and spandrel panels in vertical opaque façade panels (models 4 and 6).

The results of the calculation of installed materials indicate that models 1 and 3 exhibit the highest total weight, with façade segments exceeding 10 tons. The weigh of façade segments of models 2 and 5 is ranging from 9 to 9.5 tons, while model 4 (8.6 tons) and 6 (8 tons) have the lowest mass of built-in materials.

Among all models, the predominant contributors to overall mass of façade segments are double-glazed units in vision panels and aluminium frames. Double-glazed units constitute over 50% of the total weight of the façade segment in all models. The exception is only the base model 6, due to similar presence of vision and opaque panels in the façade.

Models 3 and 6 have a notable increase in mass of installed aluminium, gaskets and thermal breaks due to presence of window openings in the façade, offset by a substantial reduction in glass quantity. Even though the models 1 and 3 have the same façade element dimensions (1.25m wide), the second one incorporates 370kg of aluminium, 280kg of EPDM gaskets and 66kg material in thermal break more due to window presence. Conversely, model 3 has 885kg less glass, resulting in a reduced overall mass of its façade segment compared to model 1 (Table 1).

Table 1 Mass of installed materials in façade segments of models 1-6

Component / Model	1	2	3	4	5	6
Aluminium frame	1,690	1,510	2,060	1,930	1,750	2,060
DGU (Vision panel)	6,665	6,690	5,780	4,870	6,630	3,260
DGU or Spandrel panel	1,509	341	1,500	605	341	858
Insulation	439	442	439	793	442	1,130
Gaskets	188	174	467	212	205	467
Thermal break	140	126	206	179	152	205
Total weight of the façade segment (kg)	10,631	9,283	10,452	8,589	9,520	7,980

Models 2 and 5, featuring a 1.5-meter façade element width, manifest mass differentials attributed to the introduction of a more dynamic façade division. This modification elevates aluminium quantities in model 5 by 240kg compared to model 2, accompanied by an additional 55kg increase in gaskets and thermal break volumes, while other installed material quantities remain invariant.

Models 4 and 6 have the lightest configuration of façade segments owing to the inclusion of vertical spandrel panels, substituting double-glazed units with aluminium panels and insulation, thereby significantly reducing overall weight (Table 1).

The next phase of the research included the assessment of material flows based on data from the environmental product declarations obtained from the manufacturer for each component of the façade segments. Material Flow Analysis (MFA) entails tracking the input and output flows of materials during both the production and end-of-life phases of the façade component lifecycle. This analysis relies on quantifying the amount of embedded materials in kilograms, supplemented by data regarding their origins and anticipated scenarios for reuse at the end of their lifespan. MFA provides insight into the ratio of primary and secondary resources used for the production phase of façade segments. The output flows refer to the end-of-life phase, i.e. to the generated waste intended for landfill after dismantling the façade. Additionally, they provide information on the amount of material available for reuse as a recyclable resource.

Analysis of input flows reveals that models 4 and 6 exhibit the highest share of secondary materials used in the production phase of their façade segments. This outcome is attributed to the reduced transparent area of the façade compared to other models, achieved through the incorporation of vertical spandrel panels. In these models, raw materials constitute 88-89% of the total mass of façade segment, whereas in others, they represent over 91%. Consequently, in models 2, 3 and 5, secondary materials contribute to approximately 9% of the total resources utilized, primarily associated with the production processes of aluminium profiles and panels.

The lowest fraction of mass originating from secondary resources is observed in model 1, primarily due to the dominance of glass panels in the façade, whose production relies solely on primary raw materials. Consequently, this model generates the largest amount of waste (approximately 9 tons), as the anticipated scenario at the end of the glass life cycle involves landfill disposal. In this model, only 15% of installed materials are available for recycling after the dismantling of the façade segment, primarily consisting of components of the aluminium frame (Figure 5).

A slightly smaller amount of waste (8.46 tons) is generated at the end of the life cycle of the façade of model 3 due to the presence of windows, resulting in a reduced glass area. Models 2 and 5 generate approximately 7.5 tons of waste at the end of their life cycle, attributed to the possibility of recycling 95% of the aluminium from spandrel panels (Figure 5).

The generation of waste is lowest in models 4 and 6. In model 4, approximately 6.15 tons of material are disposed of in landfills (72%), while 2.45 tons are available for recycling. In model 6, approximately 2.81 tons are available for recycling (35%), while 5.17 tons of waste are sent to landfills. These two models are the most favourable in terms of materials that can be recycled at the end of their life cycle due to the larger area of spandrel panels compared to other façade segments.

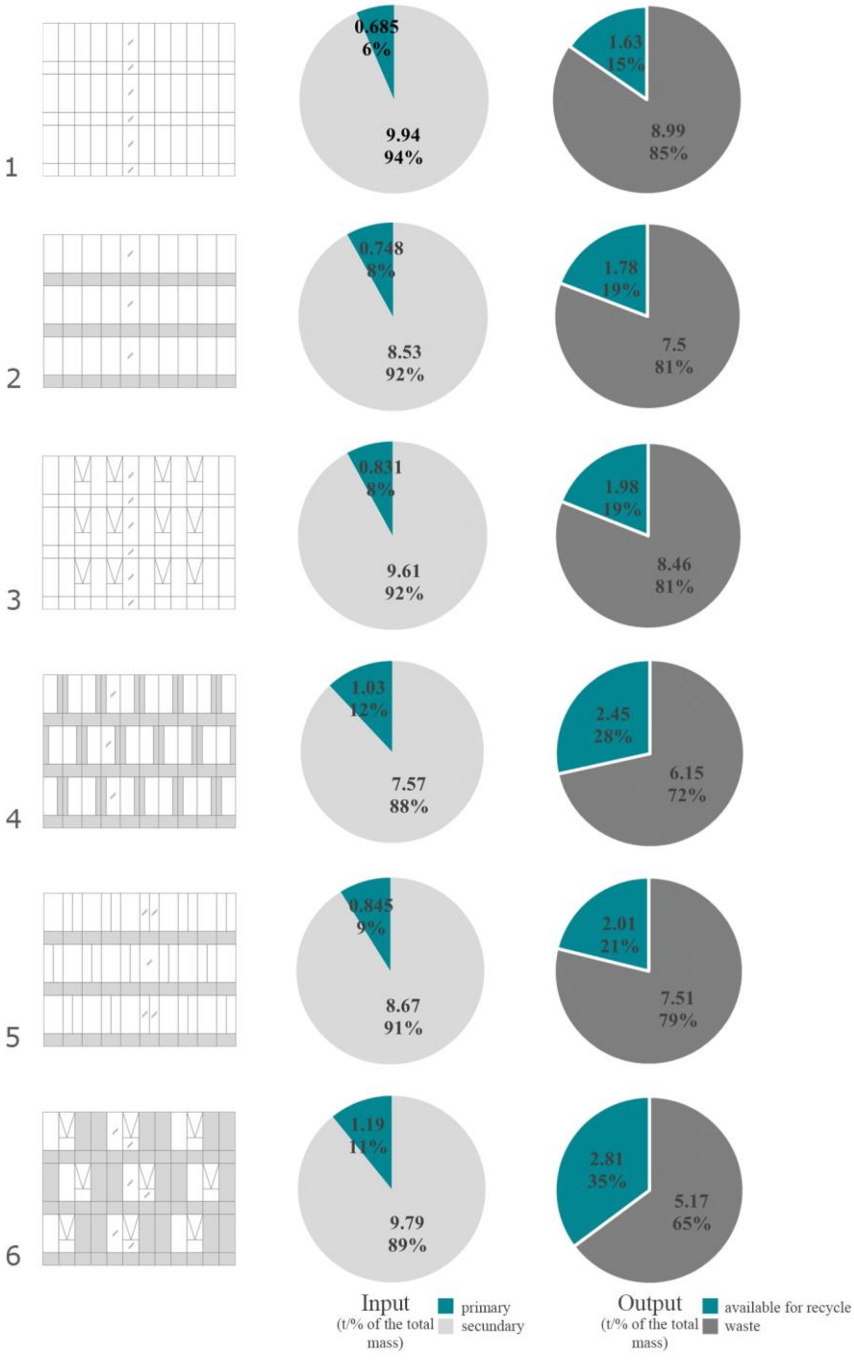

Fig. 5 Input and output flows of materials for façade models 1-6

4.2. Circularity Indicator

The previous calculation of mass of the incorporated materials depending on the architectural characteristics of the base models, serves as an input for the calculation of circularity indicator of the façade components. The indicator is calculated according to the numerical methodology outlined in Chapter 2, initially for individual components and subsequently for the entire façade segment based on their respective contributions.

The circularity indicator of individual components is influenced by the origin of materials during the production phase and the potential for their reuse at the end of the life cycle. Components with the highest circular potential include the aluminium frame (MCI=0.698) and spandrel panels (MCI=0.693), benefiting from a substantial proportion of secondary materials in the production phase and opportunities for material reuse or recycling at the end of their life cycle.

In contrast, components whose production relies predominantly on the use of primary resources have a significantly lower circular potential. Components such are double-glazed units, gaskets and thermal breaks have a circularity indicator of 0.1, whereas the value for thermal insulation is 0.12. These components are anticipated to follow a linear economy flow, ultimately ending up in landfills.

Based on the representation of components in the façade segments of models 1 to 6, the circularity indicator is calculated for both the production and end-of-life phase.

Model 6, characterized by a predominant presence of opaque panels, achieves a circularity indicator of 15% for the production phase. In model 4, where slightly more glass panels are present in the facade segment compared to fill panels, a result of 12% is achieved. On the contrary, in models where glass is present in all vertical elements of the facade as vision panel in addition to opaque panels at ceiling level, the circularity indicator is lower, specifically 8% for models 2 and 3 and 9% for model 5 (Figure 6). Model 5 exhibits a marginally higher circularity indicator compared to models 2 and 3, owing to a larger quantity of aluminium, which, from a circular potential perspective during production, proves to be the most beneficial component.

Given the dependence of the circular indicator on installed material quantity, enhancing the mass of components with individually positive Material Circularity Indicator (MCI) results leads to overall facade improvement. Consequently, model 3 achieves the same result as model 2, despite its incorporation of glass in opaque panels at the ceiling level. However, this is compensated through a higher quantity of installed aluminium in windows, thereby reducing the overall glass area. The lowest circular potential, 6% in the production phase, was recorded in model 1 due to the architectural features of its all-glass facade (Figure 6).

Results of the circularity indicator at the end-of-life phase depend on the possibility of reusing installed materials after dismantling facade segments. Improved circular potential is observed for all models in this phase compared to production phase. This is mainly due to the high reuse potential of aluminium at the end of its life cycle, when almost 95% of the originally installed material can be recycled.

Similar to the production phase, better overall results are achieved with models with a smaller glass area, as this material is the most unfavourable from the perspective of the circular potential at the end of the life cycle due to the predicted disposal of 100% of the originally installed material in a landfill.

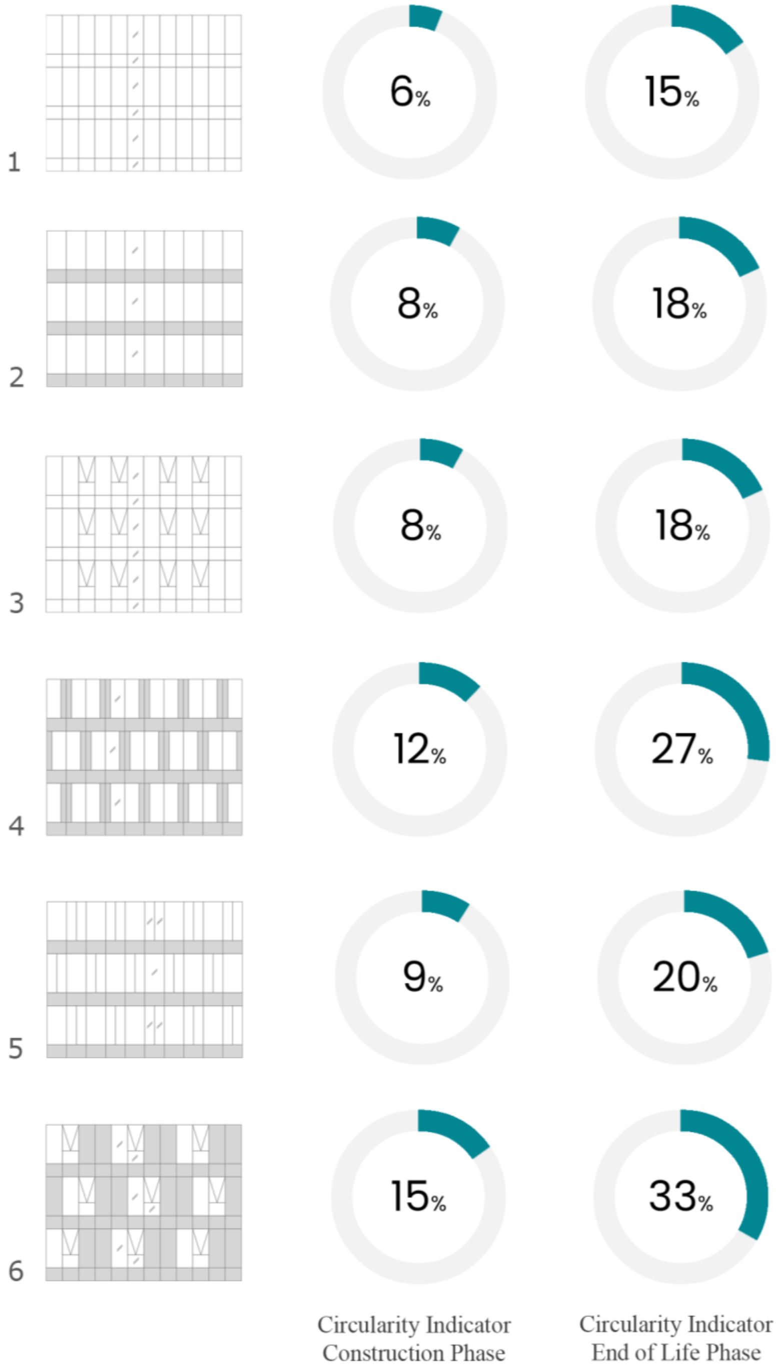

Fig. 6 Circularity indicator for the Construction and End of Life Phase for façade segments of base models 1-6

Therefore, model 6, featuring the largest aluminium quantity and the lowest glass content of all models, achieves the best result - a 33% circularity indicator at the end of the life cycle. Model 4 achieves a slightly lower result of 27% due to its higher glass quantity and narrower vertical fill panel widths compared to model 6, resulting in smaller non-transparent areas on the facade.

Substantially lower results are observed in models 2, 3 and 5, with circularity indicator scores at the end of the life cycle ranging from 18% to 20% (Figure 6). In models 2 and 5, where the width of the primary element (1.5m) and the panel infill at the ceiling level are the same, model 5 performs better due to a higher quantity of installed aluminium achieved by introducing additional element divisions in the facade segment. Despite model 3 featuring a greater amount of installed aluminium than the preceding two models, its overall circularity indicator does not improve due to the higher quantity of glass in the facade.

Similar to the results observed in the production phase, model 1 also records the lowest outcome at the end of the life cycle phase (15%), which is half of the best result achieved by model 6 (Figure 6). A comparison of these two models leads to the conclusion regarding the significance of reducing glass areas to ensure the highest circular potential at the end of the facade's life cycle.

Considering the entire life cycle of the façade segments, the total MCI for the basic models is calculated. As explained in the methodology for calculating the circularity indicator, this reference is not derived from the average between the construction phase and the end of life, since it also depends on the indicators of the components themselves and their different quantities in each of the facade models.

Given that model 6 has the most optimal circular indicators for both the production and end-of-life phases, it achieves the highest overall circularity result of 32%. Following is model 4, with an MCI of 27.8%, while the other models record significantly lower values. Due to the similarity in circular indicator values between the production and end-of-life phases in models 2, 3 and 5, their overall results fall within a similar range, from 21.8% to 23.2% (Table 2). Although models 2 and 3 share identical indicators in both the production phase (8%) and the end-of-life phase (18%), there is a difference in their overall score. Model 2 has a more favourable overall circularity indicator of 22% compared to model 3 (21.8%), due to a smaller quantity of glass in the facade segment. In accordance with the least optimal results of the circularity indicator in individual phases of the life cycle, model 1 records the lowest overall result of all facade models - 19.6% (Table 2).

Table 2 Circularity indicator for façades of base models 1-6

MCI / Model	1	2	3	4	5	6
MCI Construction Phase	6	8	8	12	9	15
MCI End of Life Phase	15	18	18	27	20	33
MCI Total (%)	19.6	22	21.8	27.8	23.2	32

4.3. CO_2 emission

The preceding calculation of the circularity indicator provided insight into the potential resource circulation throughout the life cycle of the facade segment. To comprehend the importance of facilitating this circulation of resources, their impacts on the environment are being assessed. One of the most commonly used indicators is the total global warming potential – GWP (tot), which refers to the CO_2 emissions throughout the life cycle of the entire façade segment.

The calculation of CO_2 emission was initially conducted for individual components based on their quantities, which depend on the architectural characteristics of the facade segments. The results indicate that the aluminium frame has the most significant adverse environmental impact, particularly during the production phase due to the extrusion process of the internal frame aluminium profiles and cover caps. In models 3, 4 and 6, this component accounts for over 50% of the total CO_2 emissions. The second most influential component on the overall CO_2 emission is the double-glazed units (DGU), which represent over 30% of the total emissions in models 1, 2, and 5.

Since models 3 and 6 have the largest quantity of aluminium installed due to the presence of windows, they record significantly higher CO_2 emissions compared to other models. As these two models have elements of the same dimensions and an equal number of window openings, both aluminium frame components emit 44tCO_2 each. A lower CO_2 emission originating from aluminium profiles is recorded in model 4, which lacks windows but has a larger number of vertical profiles compared to other models. This is because it features occasional additional division of basic elements, with a width of 1.5m divided into 0.75m segments. In this model, about 5tCO_2 more is emitted compared to model 2, whose basic element dimensions are the same but do not have additional division or the introduction of extra vertical elements (Table 3).

The difference in CO_2 emissions originating from aluminium in models 1 and 2 indicates that significant reductions can be achieved if wider elements are used in the façade segment resulting in a reduction in the total number of installed elements. Therefore, in model 2, where there are 30 facade elements per segment (with a width of 1.5m), a reduction of 4tCO_2 is achieved compared to model 1, which has 36 elements with a width of 1.25m.

Differences in the number of facade elements also affect the CO_2 emissions associated with seals and thermal breaks, which are reduced equivalently to the reduction of vertical frame profiles. On the other hand, the presence of windows in models 3 and 6 leads to significantly higher CO_2 emissions associated with EPDM seals (8.85tCO_2) and thermal breaks (2.97tCO_2) compared to other models (Table 3).

Table 3. CO_2 emission of components of façade segments (base models 1-6)

Component / Model	1	2	3	4	5	6
Aluminium frame	36.23	32.29	44.06	41.45	37.47	44.04
DGU (Vision panel)	20.18	20.25	17.50	14.76	20.08	9.88
DGU or Spandrel panel	4.77	3.03	4.75	5.38	3.03	7.62
Insulation	1.13	1.13	1.12	2.03	1.13	2.89
Gaskets	3.54	3.30	8.85	4.01	3.89	8.85
Thermal break	2.01	1.81	2.97	2.58	2.19	2.96
Total CO_2 of the façade segment (t)	67.86	61.81	79.25	70.21	67.79	76.24

The overall result is also significantly influenced by the ratio of transparent and opaque areas in the facade segment. Models 2, 4, 5, and 6, where opaque panels are present at the ceiling level, generally have lower CO_2 emissions than models 1 and 3, where glass is the finish covering of the entire façade segment.

In models 1, 2, and 5, DGU is associated with 20tCO_2, while this value is slightly lower in model 3 due to a smaller surface area of glass panels resulting from the addition of window frames. In facades with a more dynamic division, where the introduction of vertical opaque panels reduces the amount of installed glass, the CO_2 emission associated with this component is significantly reduced. Therefore, the CO_2 emission originating from DGU is less than 15t in model 4 and 10t in model 6.

The contribution of individual components to the total CO_2 emission for the basic models of the facade segments is highlighted in Figure 7.

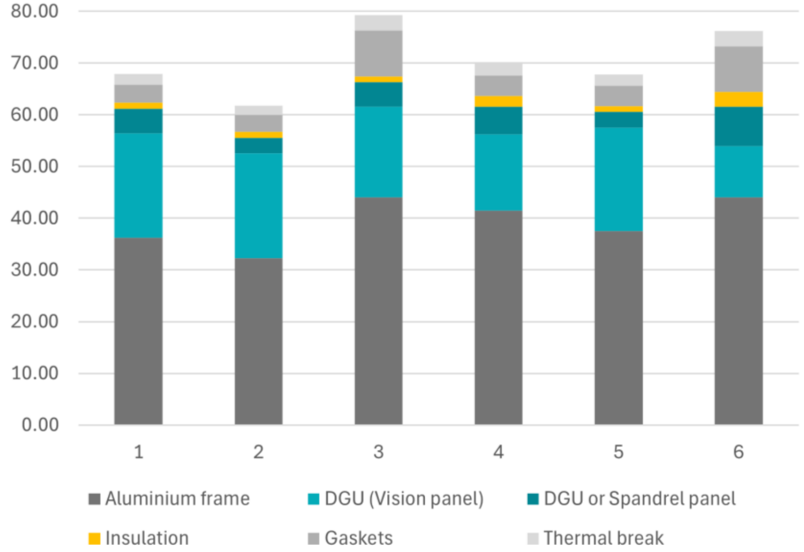

Fig. 7 Overview of the contribution of individual components to the total CO_2 emission of façade segments (models 1-6)

Based on the results of CO_2 emissions for individual components, conclusions are drawn regarding the overall emissions for each of the facade segments. The total emissions are analysed across the different phases of the life cycle:

- A - involving production and installation;
- B - refers to the use and replacement of facade elements;
- C - marks the end of the life cycle.

The results for phase D are excluded from the overall assessment due to the ongoing unreliability of calculations for this phase in the EPD declarations.

The results indicate that the highest emissions are present in models 3 (79.25 tCO_2) and 6 (76.24 tCO_2). Aluminium profiles have the greatest influence on the obtained results, especially in phases A and B of the life cycle. Although Model 6 has a significantly smaller quantity of glass than Model 3, an equal number of facade elements is primarily reflected in the quantity of aluminium, emphasizing the significant impact of this component on the total CO_2 emissions of the facade segment.

For the same reason, the best overall result is achieved in Model 2, where 61.8tCO_2 is emitted during the life cycle from Phase A to Phase C (Table 4). Although this model has the same width of the basic facade element as Models 4 and 5, the introduction of additional vertical divisions in these models results in higher CO_2 emission, totalling 70.21 tCO_2 in Model 4 and 67.79 tCO_2 in Model 5. Similarly, despite Models 1 and 3 have the same dimensions of the basic facade elements, the addition of windows in Model 3 leads to significantly higher total CO_2 emission (67.86 tCO_2).

In all models, phase C of the life cycle has a smaller impact on total CO_2 emission compared to phases A and B. The significantly higher CO_2 emission in phase C in models 3 and 6 comes from the end-of-life treatment of EPDM seals, whose mass is greater in these models due to the presence of windows (Table 4).

In phase D, the result for all models mainly originates from the recycling potential of the aluminium frame after the end of its life cycle in the facade segment.

Table 4 CO_2 emission of façade segments during the different phases of their life cycle (models 1-6)

Life Cycle Phase / Model	1	2	3	4	5	6
A	32.62	29.62	36.57	33.56	32.42	34.94
B	33.95	30.92	39.64	35.12	33.91	38.13
C	1.29	1.26	3.04	1.53	1.46	3.17
D	-26.12	-24.68	-33.43	-32.31	-28.45	-36.85
Total tCO_2 (A-C)	67.86	61.8	79.25	70.21	67.79	76.24

4.4. Potential of improvement of base models

Analysis of the facade segments of the base models has revealed that their overall circular potential is low due to the use of materials which require a significant amount of primary resources in production.

While the construction industry in Serbia has yet to embrace the principles of the circular economy, there are noticeable developments in certain construction products in the European market aligning with this concept. Therefore, ongoing research assumes that such products could soon become available in Serbia, which is why their potential benefit in the facade segments of the base models is being evaluated. Based on the analysis of the facade industry in Serbia and the characteristics of facade component production outlined in Chapter 3, the potential for optimizing the base models using products and materials available in the European market has been identified.

For each of the base models of façade segments from 1 to 6, an improved model has been assigned numbering from 1a to 6a. The improved models incorporate the use of the following components, optimized in terms of utilizing secondary materials in the production phase and having a greater potential for reuse at the end of their life cycle in the facade segment:

- For the components of the inner frame and outer cover caps, aluminium profiles produced entirely from recycled material are used. The data used for the calculation refer to the currently most optimized product available on the market from a circular economy perspective in the facade industry. These profiles are composed of aluminium recycled during various factory production processes (19.7%) and material recycled after the entire life cycle in previous products (82.1%). Data on weight and end-of-life treatment, relating to recycling potential, are consistent with those for the aluminium profiles of the base models.

- DGUs have the same assembly characteristics as the base models. Aspects such as the thickness of float glass on the inner and outer sides, filling, lamination and coating remain unchanged. The improvement concerns the origin of materials for manufacture of float glass within the assemblies of optimized models. It is assumed that 50% recycled cullet is used for glass production. In the past year, a float glass which incorporates a 64% of recycled material in its production (ORAE Saint-Gobain). Given that ORAE is the product with the highest share of secondary raw materials in the industry, the percentage of recycled material has been reduced in this research based on the assumption that a similar result will not become a general standard in the facade industry in the near future in Serbia. The production process of this glass also has a reduced negative impact on the environment due to the use of renewable energy sources. Disposal of the complete DGU component at the landfill is assumed at the end of its life cycle in façade segment.
- Mineral wool used as inventory for the numerical calculation of optimized models is characterized by improved production and end-of-life cycle phases in comparison to the one used in base models. It is a component whose production in Serbia implies significantly less use of recycled materials than the average products used in other European countries. In the improved models, the current standard for the production of these components at the European level is assumed, which includes 37% recycled material in the manufacturing phase. At the end of the life cycle, 50% of the originally installed material can be recycled, while the rest is disposed of in landfills.
- The same thickness and assembly are used for the spandrel panels, while the improvement of this component compared to the one in base models is reflected in the use of 55% recycled materials in their production. A slight improvement is also observed in the end-of-life phase, where more of the originally incorporated material is provided for further use during the recycling process.
- Gaskets and thermal breaks are the same as in the basic models, as there are still no significant improvements in the circularity of these components in the global facade industry.

According to the described improvement of materials and components, the circularity indicator and CO_2 emissions were calculated for the optimized models 1a to 6a.

4.4.1. Optimisation of Circularity Indicator

The optimisation of facade models is primarily observed in the material analysis flows. Compared to the basic models, significant improvements in material inputs are noted in all optimised models 1a-6a. In all optimized models, the proportion of recycled materials in the production phase exceeds 50%. The most significant improvement comes from increasing the fraction of recycled materials in aluminium frame components, glass and insulation.

For instance, in model 1a, the total use of secondary materials amounts to 56%, or 5.94t, compared to 0.685t in the base model 1. Similarly, in model 2a, the share of secondary materials in production is 56%, or 5.2t, in contrast to only 0.748t in the base model 2. The same percentage of recycled material is observed in model 3a (5.86t). The most significant improvement is achieved in model 4a, where 58% of the material mass originates from secondary sources, approximately 5t, as opposed to just 1t in the base model 4 (Figure 8). In models 5 and 6, recycled materials constitute 57% of the total mass of the facade segment, representing a significant improvement compared to base models 5 (9%) and 6 (11%).

Corresponding to the increase in the use of recycled materials in the production phase observed in the material flow input analysis, the circularity indicator of all improved models is also increased. It reaches 56% in models 1a, 2a, and 3a, and 57% in models 5a and 6a. The best result is attained in model 4a, where the circularity indicator reaches a value of 58%, marking a significant improvement compared to the base model 4 (12%). The most significant improvement in MCI is achieved in model 1a, due to the increased use of recycled material in the production of glass, the component that has the greatest impact on this model's circular potential (Figure 8).

Results of the circularity indicator in the production phase of improved models indicate a significant potential for optimizing the overall circularity of facade segments by using improved materials. However, less improvement is observed in the end-of-life phase. Models 1a, 3a, and 5a achieve a 2% improvement over the base models, while model 2a attains a 3%. The slight improvement in the amount of material available for reuse at the end of the life cycle comes from the fact that glass, which makes up the largest proportion of the mass of all facade segments, is expected to be landfilled (as was the case with the base models).

Accordingly, a slightly greater improvement in output material flows is noticeable in models with a smaller amount of glass and the presence of vertical opaque panels. For instance, model 4a achieves a 5% improvement in the amount of material available for reuse at the end of the life cycle compared to the base model 4. In model 6a, this improvement is even greater - 7%, due to the larger surface area of opaque panels (Figure 8).

Reflecting the significant optimization of the circularity indicator in the production phase across all models, an improvement in the overall MCI is observed. All optimised models show improved total circularity indicator, with model 6a achieving the best result of 54.2%, followed by model 4a (MCI=45.6%) as shown in Table 5.

Table 5 Circularity indicator for façades of improved models 1a-6a

MCI / Model	1a	2a	3a	4a	5a	6a
MCI Construction Phase	56	56	56	58	57	57
MCI End of Life Phase	16	20	20	31	22	40
MCI Total	42.5	44.4	44.2	50.5	45.6	54.2

Compared to the base models, the more significant improvement is achieved in models 2a, 3a and 5a, which demonstrate a doubling of the value. The higher improvement in these models is due to the use of 50% recycled material in the production of DGU, which are predominant compared to other components in these models. Consequently, model 2a achieves a result of 44.4%, compared to 22% in model 2. The same improvement ratio of the total circularity indicator is achieved in model 3a (MCI=44.2%) compared to 3 (21.8%). Thanks to significant improvement in the circularity potential in the production phase, model 4a achieves a MCI of 50.5% compared to 23.2% in model 5 (Table 5). Overall, the greatest improvement is observed in model 1a, which generally has the lowest circular potential. In model 1a, the MCI is 42.5% as shown in Table 5, representing a significant optimization of the overall circular potential compared to the base model 1 (MCI=19.6).

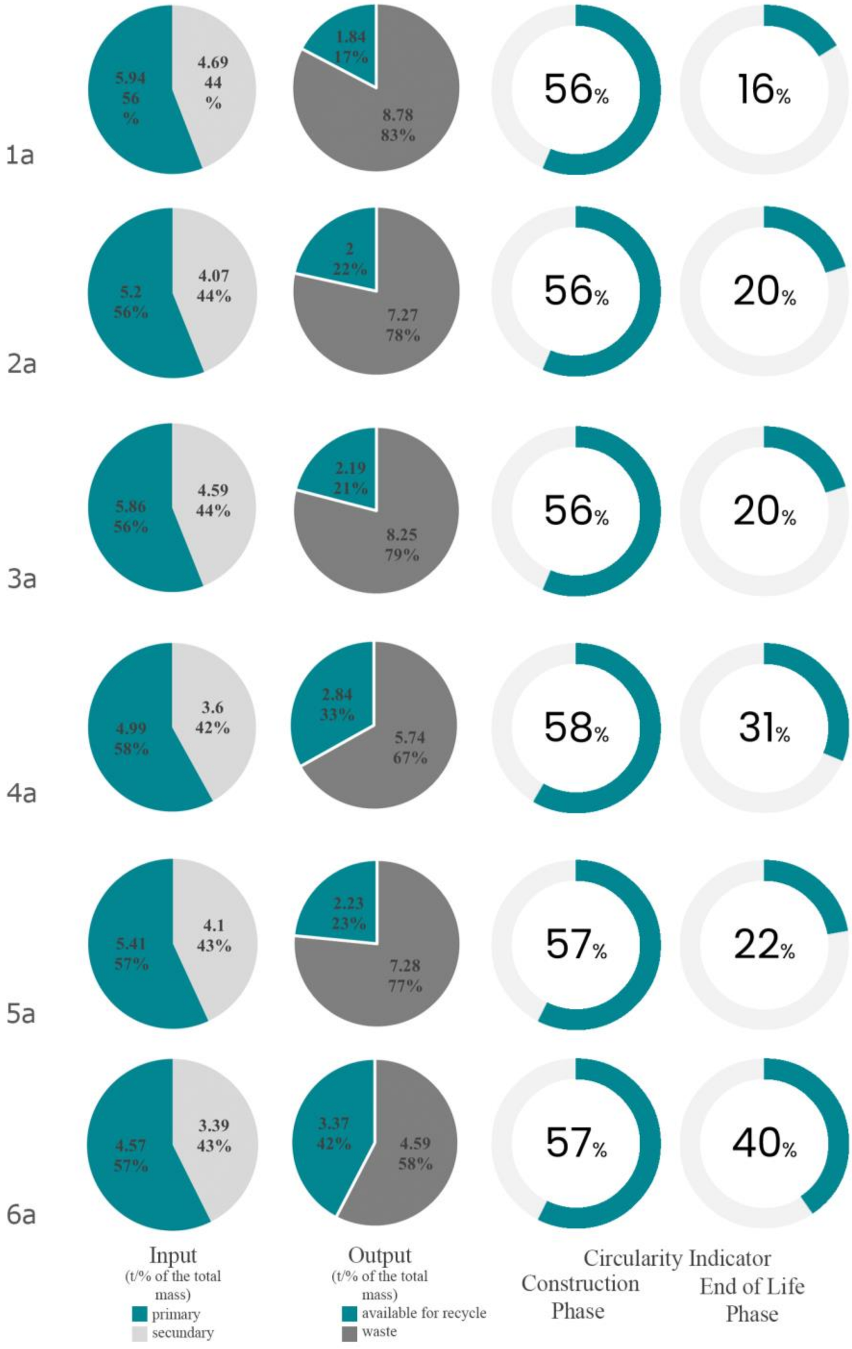

Fig. 8 Circularity indicator for the Construction and End of Life Phase for façade segments of improved models 1a-6a

4.4.2. Optimisation of CO_2 emissions

The selection of materials incorporating recycled materials and sourced from renewable energy significantly reduces CO_2 emissions in the improved models. The greatest impact on CO_2 reduction in all models comes from the use of aluminium profiles made entirely from recycled materials, as the CO_2 emissions for this component in the improved models are reduced by up to three times compared to the base models. The CO_2 emissions attributed to aluminium are lowest in model 2a at 11tCO_2 and highest in model 6a at 15tCO_2, marking a significant reduction compared to base models 2 and 6.

Furthermore, the reduction of CO_2 in the improved models is also contributed using glass whose production process involves the use of renewable energy sources, resulting in a 30% decrease in total CO_2 emissions attributed to this component. This achieves the lowest CO_2 emissions attributed to this component in model 6a – at 9.88 tCO_2, and the highest in models 1a, 2a, and 5a – around 13.5 tCO_2. The optimization of insulation materials also plays a significant role, with emissions of this component reduced by 50% in the improved models compared to the base models (Table 6).

Table 6 Global warming potential of components of façade segments in tCO_2 (improved models 1a-6a)

Component / Model	1a	2a	3a	4a	5a	6a
Aluminium frame	12.34	11.00	15.01	14.12	12.77	15.00
DGU (Vision panel)	13.62	13.67	11.81	9.96	13.55	6.67
DGU or Spandrel panel	3.28	1.25	3.25	2.21	1.24	3.13
Insulation	0.67	0.68	0.67	1.22	0.68	1.72
Gaskets	3.54	3.30	8.85	4.01	3.89	8.85
Thermal break	2.01	1.81	2.97	2.58	2.19	2.96
Total CO_2 of the façade segment (t)	35.46	31.71	42.56	34.10	34.32	38.33

In all improved models, as with the base models, the aluminium frame profiles and DGUs in vision panels have the greatest impact on total CO_2 emissions as highlighted in Figure 9.

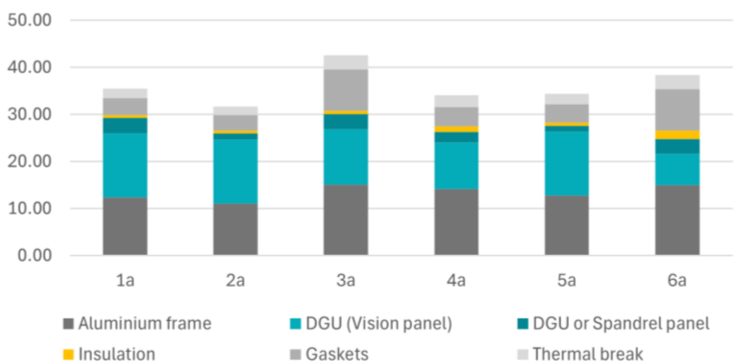

Fig. 9 Overview of the contribution of individual components to the total CO_2 emission of façade segments of improved models 1a-6a

The optimization of selected materials leads to a reduction of about 50% of CO_2 emissions in phases A and B of the life cycle, while changes in phase C are minimal. The best result is achieved in model 2a with a total CO_2 emission in phases A-C of 31.71tCO_2, followed by models 1a, 4a, and 5a with total CO_2 emissions of 34-35 tCO_2. Models 3a and 6a exhibit higher CO_2 emissions due to a greater quantity of installed aluminium and the presence of window openings. The CO_2 emissions for model 4a amount to 42.56tCO_2, while they are slightly lower for model 6a at 38.33 tCO_2 (Table 7).

Table 7 CO_2 emission of façade segments during the different phases of their life cycle (improved models 1a-6a)

Life Cycle Phase / Model	1a	2a	3a	4a	5a	6a
A	16.36	14.57	18.15	15.54	15.68	16.07
B	17.74	15.86	21.29	17.06	17.17	19.17
C	1.36	1.27	3.12	1.5	1.47	3.09
D	-6.03	-7.23	-9	-10.13	-8.12	-13.58
Total CO_2 (A-C) (t)	35.46	31.7	42.56	34.1	34.32	38.33

The greatest reduction in total CO_2 emissions of 37.91tCO_2 is achieved in model 6a compared to the base model 6, attributable to its extensive use of aluminium and larger opaque vertical panels, whose components demonstrate significant improvement in circular potential in model 6a. Models 3a and 4a also achieve significant reductions of around 3 tCO_2 compared to the base models, thanks to the optimization of aluminium profiles and DGUs in vision panels. Models 1a and 5a achieve a reduction of approximately 33 tCO_2 compared to models 1 and 5, primarily due to the use of aluminium profiles made entirely from recycled material. The smallest optimization of CO_2 emissions of 30.1t is achieved in model 2a compared to model 2, as this model was already the most favourable in terms of CO_2 emissions from the start. The total CO_2 emission reduction achieved in the improved models compared to the base models is shown in Figure 10.

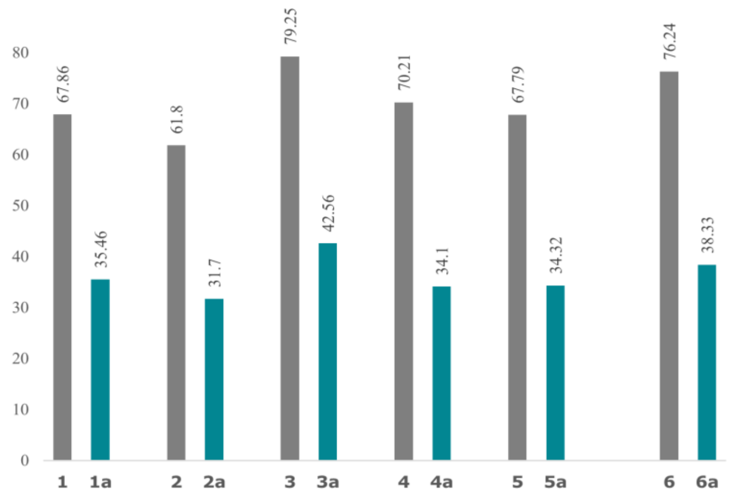

Fig. 10 Comparison of total CO_2 emission of base models 1-6 with improved models 1a-6a

In summary, all improved models achieve about 40 to 50% reduction in total CO_2 emissions in phases A-C of the life cycle of the façade segments compared to the base models (Figure 10).

4. DISCUSSION AND CONCLUSION

Considering material input and output flows conclusions are drawn about primary and secondary resource quantities for each façade segment of defined models. The possibility of reuse at the life cycle end is estimated, along with quantities disposed of as waste or returned in manufacturing process as resources. Based on the results, it can be concluded that optimal results are achieved in facades featuring lower proportion of transparent areas, due to the negative impact of DGU on input and output flows. Additional quantities of aluminium in models of façade segments with window openings or in models with narrower elements negatively impact the use of raw materials in the production phase. On the other hand, they have positive impact on the end-of-life cycle phase because, as around 95% of installed material can still be recycled. Opaque horizontal or vertical panels positively affect both production and end-of-life phases, with aluminium panels offering more favourable recycling potential than glass units.

The calculation of circularity indicator for the production phase indicates that the most favourable outcomes occur with models featuring reduced glass quantities compared to others. Therefore, the optimal outcomes are attained in models 6 and 4 due to their incorporation of vertical opaque panels and the resultant reduction in installed glass. Larger areas of non-transparent panels within the facade segment contribute to this outcome because spandrel panels are more favourable than glass from a circular potential perspective at the end of the life cycle.

It can be concluded that the components with the greatest impact on the circular potential in the production phase are DGU and aluminium frame. While the increase of glass quantity has a negative impact on the circularity indicator, increasing the quantity of aluminium has a positive influence due to the presence of recycled materials in the production of these components. Additionally, the circularity potential of the facade segments can be improved by installing vertical opaque instead of vision panels due to the higher amount of recycled materials in the thermal insulation and spandrel panels compared to DGU. Furthermore, it can be concluded that seals and thermal breaks have a minimal influence on circular potential. Changes in the installed quantity of these components, which are unfavourable from the circular potential perspective, are negligible compared to the impact of aluminium frame components, double-glazed units and spandrel panels.

The assessment of circularity indicator and CO_2 emissions indicates that components with the greatest influence on the circular potential of façade segments are aluminium profiles and double-glazed units. In the calculation of the circularity indicator, it was found that the increase in the mass of installed glass had a negative effect on the overall result, while an increase in the aluminium component had an opposite effect. On the other hand, aluminium had a significantly large impact on CO_2 emissions, whereby the increase in the amount of this component resulted in significantly unfavourable CO_2 emissions of the entire segment of the facade. Furthermore, models incorporating vertical opaque panels in the façade segment demonstrate better outcomes.

These results highlight the importance of assessing the circularity potential of high-rise building facades using various indicators, since the model that appears most optimal in terms of circularity indicators may not necessarily be the most optimal in terms of CO_2 emissions.

Considering the findings of presented research, it can be concluded that improvement of materials such are aluminium, glass, insulation and spandrel panels could improve the overall circular potential of facades of high-rise buildings in Belgrade. The assessment indicated that the optimization of circular potential of facades could be achieved through selection of materials produced with a higher quantity of recycled resources materials using recycled materials and improved environmental impacts. It is assumed that the further improvement of circular potential of facades high-rise buildings could be achieved through optimisation of disassembly process of façade components and the extension of their life span, which will be the objective of future research.

Considering that the design of the facades of high-rise buildings is strongly influenced by the architectural concept, it is necessary for architects to consider the concept of circular economy in the planning phase in order to enable the optimization of resource consumption and negative impacts to the environment throughout the whole life cycle of facades as well as entire buildings.

REFERENCES

1. N. Hollister, "The History of European Skyscraper," CTBUH Journal, vol. 2, pp. 52-55, 2013.
2. O. Asendorf, Ed., Das Hochhaus und die europäische Stadt, Bonn: Bundesamt für Bauwesen und Raumordnung, 2005.
3. J. Eisele and E. Kloft, Eds., High-rise Manual: Typology and Design, Construction and Technology, Basel, Boston, Berlin: Birkhäuser Architecture, 2003.
4. J . Đorđević-Ciganović and V. Mihaljević,Pogled na Beograd sa visine, INFO, vol. 33, pp. 9 -51, 2011.
5. V . Aničin i R. Mišić, Koliko visoko teži Beograd, Urbanizam Beograda, 38/39, pp. 41 -48, 1977.
6. K. Yeang, The Green Skyscraper: The Basis for Designing Sustainable Intensive Buildings, London, New York: Prestel Publishing, 1999.
7. K. S. Moon, "Dynamic Interaction between Technology and Architectural Aesthetics in Tall Buildings, Journal of Urban Technology, vol. 20, no. 2, pp. 3-24, 2013.
8. F. Navaei, "An Overview of Sustainable Design Factors in High-Rise Buildings," International Journal of Science, Technology and Society, vol. 3, no. 2-1, pp. 18-23., 2015.
9. J. F. Straube and E. F. P. Burnett, Building science for building enclosures, Westford: Building science press, 2005.
10. Arup, Carbon Footprint of Facades: Significance of Glass, 2022.
11. D. Clark, What Colour is your Building? Measuring and reducing the energy and carbon footprint of buildings, London: RIBA Publishing, 2012.
12. R. Hartwell, S. Macmillan and M. Overend, "Circular economy of façades: Real-world challenges and opportunities," Resources, Conservation & Recycling, vol. 175, 2021.
13. Bechmann, R., & Weidner, S. (2021). Reducing the Carbon Emissions of High-Rise Structures from the Very. CTBUH Journal, 4, 30-35.
14. D. Trabucco, A. Wood, N. Popa, O. Vassart and D. Davies, Life Cycle Assessment of Tall Building Structural Systems, Council on Tall Buildings and Urban Habitat, Chicago., 2015.
15. T. Berger, P. Prasser and H. G. Reinke, "Einsparung von Grauer Energie bei Hochhäusern," Beton- und Stahlbetonbau, vol. 108, no. 6, pp. 395-403, 2013.
16. C. Drew and N. Q. Quintanilla, The Path to Life Cycle Carbon Neutrality in High Rise Buildings, International Journal of High-Rise Buildings, vol. 6, no. 4, pp. 333-343, 2017.
17. R. Giordano, M. Giovanardi, G. Guglielmo and C. Micono, Embodied energy and operational energy evaluation in tall buildings according to different typologies of façade, Energy Procedia, vol. 134, p. 224–233, 2017.

18. F. Pomponi and A. Moncaster, "Circular economy for the built environment: A research framework," Journal of Cleaner Production, vol. 143, pp. 710-718, 2017.
19. P. Mhatre, V. Gedam, S. Unnikrishnan and S. Verma, "Circular economy in built environment – Literature review and theory development," Journal of Building Engineering, vol. 35, 2021.
20. M. Geissdoerfer, P. Savaget, N. M. P. Bocken and E. J. Hultink, "The Circular Economy – A new sustainability paradigm?," Journal of Cleaner Production, pp. 757-768, 2017.
21. D. Baker-Brown, The Re-Use atlas: A designer's guide towards a circular economy., RIBA Publishing, 2017.
22. K. Guldager and J. Sommer, Building a circular future., Hvidovre: The Danish Environmental Protection Agency, 2016.
23. Ellen MacArthur Foundation, Growth within: A circular economy vision for a competitive Europe., 2015.
24. J. Korhonen, A. Honkasalo and J. Seppälä, "Circular Economy: The Concept and its Limitations," Ecological Economics, vol. 143, pp. 37-46, 2018.
25. S. Vanhamäki, S. Rinkinen and K. Manskinen, "Adapting a Circular Economy in Regional Strategies of the European Union," Sustainability , vol. 13, no. 1518, 2021.
26. European Commission, Circular economy action plan: for a cleaner and more competitive Europe, Publications Office of the European Union, 2020.
27. T. Weber and M. Stuchtey, "Deutschland auf dem Weg zur Circular Economy – Erkenntnisse aus europäischen Strategien (Vorstudie)," Deutsche Akademie der Technikwissenschaften, München, 2019.
28. Ministry of Environmental Protection, Roadmap for circular economy in Serbia,2020.
29. D. Cheshire, Building revolutions applying the circular economy to the built environement, Newcastle upon Tyne: RIBA Publishing, 2016.
30. S. Brand, How Buildings Learn: What Happens After They're Built, New York, United States of America: Viking Press, 1994.
31. B. Berge, The Ecology of Building Materials, London: Routledge, 2009.
32. A. M. Memari, Curtain Wall Systems: A Primer, Reston: American Society of Civil Engineers, 2013.
33. R. Hartwell and M. Overend, "End-of-Life Challenges in Facade Design: A disassembly framework for assessing the environmental reclamation potential of facade systems," in Façade Tectonics World Congress 2020 Conference, 2020.
34. A. L. Binow Bitar, I. Bergmans and M. Ritzen, "Circular, biomimicry-based, and energy-efficient façade development for renovating terraced dwellings in the Netherlands," Journal of Facade Design and Engineering, vol. 10, no. 1, pp. 75-104, 2022.
35. M. K. Kragh and N. Jakica, "Circular economy in facades," in Rethinking Building Skins: Transformative Technologies and Research Trajectories, Woodhead Publishing, Series in Civil and Structural Engineering, 2022, pp. 519-539.
36. M. Saidani, B. Yannou, Y. Leroy, F. Cluzel and A. Kendall, "A taxonomy of circular economy indicators," Journal of Cleaner Production, vol. 207, pp. 542-559, 2019.
37. P. Dräger, p. Letmathe, L. Reinhart and F. Robineck , "Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database," Environmental Sciences Europe, vol. 34, no. 13, 2022.
38. A. van Stijn, L. Malabi Eberhardt, B. Wouterszoon Jansen and A. Meijer, "A Circular Economy Life Cycle Assessment (CE-LCA) model for building components," Resources, Conservation and Recycling, vol. 174, 2021.
39. Ellen MacArthur Foundation, "Circularity Indicators: An Approach to Measuring Circularity. Methodology.," 2019.
40. F. Heisel and S. Rau-Oberhuber, "Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster," Journal of Cleaner Production, vol. 243, no. 118482, 2020.
41. Madaster, "Madaster Circularity Indicator," 2021.
42. Madaster, "Madaster User Manual: General user guide of the Madaster Platform," 2022.
43. R. Crawford, Life Cycle Assessment in the Built Environment., Abdingdon, Oxon: Spon Press, Taylor & Francis group, 2011.

PROCENA CIRKULARNOG POTENCIJALA FASADA VISOKIH OBJEKATA U BEOGRADU

U Beogradu je trenutno primetna izgradnja većeg broja visokih objekata, kojih je tokom prethodne decenije izgrađeno više nego u prethodnih 50 godina. Visoki objekti zahtevaju primenu specifičnih tehnologija gradnje koje se povezuju sa značajnom potrošnjom resursa i energije, čime oni imaju izuzetno negativan uticaj na životnu sredinu. uticajima građevinske industrije na životnu sredinu. Cilj istraživanja je procena mogućnosti smanjenja potrošnje resursa za izgradnju ovih objekata, uz fokus na cirkularni potencijal njihovih fasada. Primenjena metodologija za procenu cirkularnog potencijala fasada se zasniva na numeričkom proračunu cirkularnog indikatora materijala i emisije ugljen-dioksida. Na osnovu rezultata istraživanja izvode se zaključci o cirkularnom potencijalu na početku i kraju životnog ciklusa fasada, odnosno fazama proizvodnje, demontaže i odlaganja ugrađenih komponenti. Istraživanje ukazuje na razlike u količini utrošenih resursa u zavisnosti od arhitektonskih karakteristika ispitivanih fasada, i daje smernice za njihovo unapređenje kroz primenu materijala koji su optimalniji sa stanovišta cirkularne ekonomije i uticaja na životnu sredinu.

Ključne reči: *cirkularna ekonomija, indikator cirkularnog potencijala materijala, reciklaža, ponovna upotreba, kraj životnog ciklusa zgrada*, *emisija* CO_2

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A CONCEPTUAL FRAMEWORK FOR POSITIONING THE ARCHITECT WITHIN A CONTINUAL DIGITAL APPROACH TO DESIGNING ARCHITECTURE: THE "DIGITAL CHAIN" CASE

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Abstract. *Studying the development of digital technology in architecture during the last thirty years highlights the opportunity for exploring the process of positioning the architect within an architectural approach based on the continual digital data-driven design and realization, using the example of the "digital chain" principle. Digital tools and processes have evolved driven by technological advancements and supporting the architectural design, but also challenging the influence and role of the architect as designer.*
Accordingly, the positioning of the architect within the design and realization of architecture is a process that constantly is developing, evolving, progressing and changing, but not simultaneously with the development of technology. The paper investigates this with the focus on the "digital chain", which is the continual approach that links architectural design and realization by coding the process and involving digital fabrication (machine and material) and the architect in each step of architectural accomplishments.
Methodologically, this research is based on overlapping the information of a (rapid) review of the continual digital data-driven design principle (example of "digital chain") over time and the conventional (analog) design focused both on architect's discourse, role and influence in the current and future design and implementation of works of architecture. The paper does not define the exact position of the architect in the "digital chain" because the process is further evolving and also depends on the type of fabrication, taking into account the freedom of choice of the architect. It does, however,

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identify the zone and type of influence of the process effects on the architect, and determines the necessity and role of the architect as a designer in the process.
The work aims to define and outline the currently developing conceptual framework of the positioning of architects, while a precise definition of the position would hinder the architect from expressing creativity. However, new research directions open a scientific field of constant redefinition of the design process with architectural influence in terms of activities and characteristics of the role of the architect within continual digital approaches to designing architecture.

Key words: *emerging architecture, positioning of the architect as designer, redefinition of the design process, continual data-driven design*

1. Introduction

Today, architectural design and realization cannot be considered separately from the emerging architecture based on digital technology. Digital technology is a tool that enables the translation of ideas into reality by incorporating approaches such as the introduction of manufacturing into the conceptual development of the architectural process (Markovic, 2016). Due to the increasingly high technical complexity of buildings and the urgent need to reduce the environmental impact of the built environment, digital tools and processes are now inevitable in the design and realization of contemporary architecture

Regarding the overall understanding of digital culture, it is necessary to examine the changes and the formation of transformations and cultural forms of different processes – phenomena (Miller, 2011). Technology is already moving on from a data-driven design to artificial intelligence (AI) with a swiftly increasing number of digital design and decision-making tools, especially for implementation, such as BIM. Most architects are still adapting to digital design environments and consequently the new ways of thinking and designing that come with them. Acceptance of technology, digital tools and the knowledge that they encapsulate enables or disables the architect in the design process (Witt, 2010). In this context, it is crucial to reflect on the possible future role of the architect as designer, human agent, with specific personal skills and abilities based on natural intelligence (Cross, 2011).

From the perspective of the digital theory, the term *context* takes on a new meaning. It is created for the code of an artificial environment, where the selected parameters influence and define the digital design (Markovic, 2020). In short, coding is now the context and a fundamental means of producing digital design. This new context, as a setting for the (dis)positioning of architects, filters and demystifies the intersection of the dual approach processes (digital and conventional) based primarily on the explanations by Bryan Lawson and the special treatment of material and machines through the architect's discourse.

The connection between architecture and digital technology exists, but today's technology inappropriately assumes, in certain segments, the primary role of guiding the architectural idea. In this way, it seems that the context – digital environment, human – “architect, user, and artifact – of both the design and the house should be questioned in both position and scope” (Markovic, Nikezic, 2023). The paper approaches the subject of the position of the architect in architectural design and realization processes using the “digital chain” as an example of a continual digital approach. The “digital chain” refers to a digital design process in architecture supported at every step by a computer that comprises the design assignment, the approach to the design assignment, and the design-to-production. The concept is explained and researched by Prof. Dr. Ludger Hovestadt, CAAD Chair[1] at the ETH Zurich. Today, “digital chain” expands to include digital architectonics with topics like encoding, coding and decoding overlapping with social realms – sacred, public and private (Hovestadt, 2023).

The development of the “digital chain” from the design to production by architectural discourse could be followed with a rapid review over time – from the example of the Monte Rosa mountain shelter (Dohmen and Rüdenauer, 2007); through the testing of the “digital chain” considered as paradigm (Loveridge, 2012), the redefinition (Markovic, Svetel, Lazovic, 2017) and experience (Cvetic and Markovic, 2017) of architectural design based on it. The topic has been further extended to include the creation of a knowledge base in monitoring as part of Industry 4.0 (Meski at al,2019), the virtual reality of hand gestures (Numfu at al, 2020), the internet-of-things (Sakshi and Sharma, 2023) and kinematically redundant robotic system (Subrin at al, 2019).

Similarly, the issues of structural integrity and life span is placed in the context of today’s circular construction method. Considering the complexity of architectural requirements and general issues of design and realization, sustainability, maintenance, durability and recycling in emerging architecture, the topic of the integrity and life of architectural structures is highly topical. Architectural spaciousness, as a creative activity and durability of construction in terms of careful and complex design of the structure, has a multi-layered networked - common effect (Markovic, 2020). The circular construction could be explored and expanded from the basic principles of the “digital chain” and extended in its scope.

With the development of digital fabrication, the next step in circularity could also be robotically assembled structures based on a material processing technology (Mangliar and Hudert, 2022).

Digital design thinking, as “the core creative process for any designer” (Cross, 2023) is still an evolving process in the emerging architectural design and practice. As an emerging essence, the competence of design thinking has become critical in the inclusion to the discourse, which includes computer science as a necessary component of the building process and clearly demonstrates the continued value and emphasis on the participation and collaboration of all interested parties. It opens an opportunity for a diverse group of individuals from many aspects of architecture and engineering community, the opportunity to investigate and innovate through collaboration on potential design projects with a focus that ranges from a more inclusive, industry-focused approach to identifying the challenges of the event (Peters and Peters, 2013). The increasing involvement of the user and other stakeholders in participatory or co-design reduces the creative influence of the architect (Markovic and Nikezic, 2023) and makes the process less continual.

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[1] http://www.caad.arch.ethz.ch/blog

"The CAAD Chair (Computer aided architectural Design) under the leading rule of Prof. Hovestadt at the ETHZ developed prototypes of “Digital Chain of Production”. The aim of this work is to show the process of design and building, which is in every step supported by computers and whose interfaces are digital. A “Digital Chain” is an uninterruptible digital process from the design (structure and form finding), over the construction (detail) to production (CNC- fabrication (manufacture)). Every step is a programmed entity, which are connected by universal interfaces. The computer does not appear like a passive digital drawing board, but like an active design controlled work tool. Rules, connections and aims are verbalized by architects, who can make optimizations of a number of different variants as a result of the computing power of a computer. *The role of architects moves from a designer of form to a designer of process. The Aesthetic of results is sometimes exciting and exceptional, sometimes organic and self-evident… it is always the result of specified parameters.*

There are three crystallized topics, which could have influence on the contemporary architecture: efficiency, complexity and refinement."

The theoretical stance of this paper approaches the concept of human drivers (Colomina and Wigley 2016/2022) as uncontrolled, fluid parameters in the algorithm of future relationships in data-driven, continual architectural design and realization processes. They are process connectors, as “man and machine are components of the communicational model” (Vrachliotis, 2022). The continuity is lost without “natural intelligence” (Cross, 2001) and the process result of human activity towards “architectural materiality” (Picon, 2020). Furthermore, the paper approaches digitally or computationally enhanced design thinking as an extension of Nigel Cross's understanding and exploration of natural intelligence as part of AI. Cross uses the latter as a testing ground for better understanding its natural counterpart.

The research aims to propose the “digital chain” as an efficient, complex, specific and defined design process based on the characteristics of different materials, which continually leads to the limited series of automated architectural realization. According to Fleischmann and Menges the form, material and structure have been analyzed and generated together as part of design in order to create complex relationships and achieve a common result with the requirements of fabrication. The process is controlled by the creative contribution of the architectural profession in every part of the architectural chain. The standardization of architectural education takes place through the adoption of digital design approaches (Chiu, 2006). Future architects can improve the connection between design and realization based on the technological discourse in architecture and lead to computational/informational changes in society (Miller, 2011).

2. Context for the Modified Role of the Architect as an Overlap between Conventional and Digital Approaches to Architectural Design – the “Digital Chain” Principle

Emerging architecture, a contemporary architectural reality, is represented by various architectural products created in simultaneously running design and realization processes using conventional, digital or combined tools. In response to a complex context and the requirements of emerging architecture itself, an experimental mode based on the digital approach is required. It involves experimentation and change beyond the prototype phase to test the whole process, from design to fabrication, including production, materials, and the machine. These constant changes in the process trigger the change in the positioning of the architect (Markovic, 2016).

The impact of digital technology on the development and behavior of the architectural process, and the theoretical and practical research of computer numerical controlled (CNC) technology in the architectural realm, is most apparent in the overlap with conventional design and realization experience (based on “demystification of architectural process” by Lawson, 2004, 2005, 2009). The conventional architectural design and realization process is driven by the preliminary design of the design task, the personal vision of the architect. The process is linear and consists of design parts and manufacturing architecture based on the architect’s methodology, trust, knowledge and experience. The architectural chain, thus, comprises ideas, projects, models, development and realization in single collaborative circles and a common line (see Fig. 1,1a).

Each project deeply embeds components of design thinking through long-term mental processes based on controlled conditions, team conversation and work media. The role of the conversation is essential as a verbal idea description as the design thinking begins with the discussion. “True creativity begins where language ends” (Lawson, 2004), while the integrity of the architect's knowledge, the designer's expertise, is its inevitability and a complex collection of skills (Lawson, Doorst, 2009). In conclusion, the architect possesses expert knowledge of interdisciplinary teamwork that offers collaborative values to all participants in the mutual process.

The digital process is an upgraded version of the conventional chain in architecture. It engages computational tools developed for design solutions to meet complex requirements while imposing certain architectural constraints. (see Fig. 1,1b). The digital process is commonly used in architecture to handle multiple, variable architectural and contextual parameters. The resultant complexity is not always related to pursuing geometrically complex forms. Instead, it emerges from the complexity of the building’s concept, appearance, and construction and the complexity of the relationships that are fundamental to the digital architectural process (Markovic, 2013). In short, the complexity of its emergent forms is not necessarily a pursued design intent but an intrinsic by-product of the digital process’s contextual engagements (Miodragovic, 2019).

The design assignment is the beginning of the “digital chain” that provides input to the entire digital design process. The demystification of the “digital chain” is done by explaining the components of the process as *links and connectors* (Markovic, 2013), their overlap or divergence from the conventional architectural design and realization, and their manifestation through the practical use in architecture. *Links* refer to differently organized and represented sub-processes in the “digital chain” (see Fig. 1). They include the approach to design assignment, digital design (coding), Realization 1 (production of prototypes) and Realization 2 (production of structure). They occur individually, as a part of the chain, and are influenced by several *connectors*. *Connectors* are derived from the interactivity of complex architectural design and realization processes. They represent disruptions of the chain's linearity instigated by internal and external influences to achieve design assignment and digital design (coding). They include influences from machines, material properties, and fabrication, such as transport tools and assembly requirements. The end of the chain refers to the post-production phase linked to the presentation and confirmation of structures. The “digital chain” in architecture is set as a principle of connected design and realization through coding in terms of the complexity of parallel codes in the completed product.

Furthermore, the more recent context is the communication of the programming parameters through coding. Emerging architecture is also a product of the overlap between technological tools and their context, the connection between multiple complex requirements, and the architect’s approaches and actions with a meaningful connection to the product, i.e. space. The architect is, thus, a code creator for product creation, and the design process is a harmonization of the context and functions as spatial results, forms that fulfil the architect’s aesthetic criteria (see Fig. 2).

At the heart of conventional architectural approaches lies the drawing that predicates the notational sameness between the architect’s intention and the realization of this intention into a spatial object (Carpo, 2011). Here, the architect codified the form. In the new context, the architect encodes the formation of the form, a set of architectural processes from the design intent until realization (Miodragovic, 2019). More recent approaches driven by the technological significance of interactive architectural design and realization require, from a sociological perspective, interactivity between subjects. These include participants in the architectural process, who carry the idea, external and internal influences, and the modelling and implementation of prototypes into the final product, the architecture. The core purpose of architecture remains unchanged, but its process and the roles of participants change significantly (Markovic, Svetel, Lazovic, 2017).

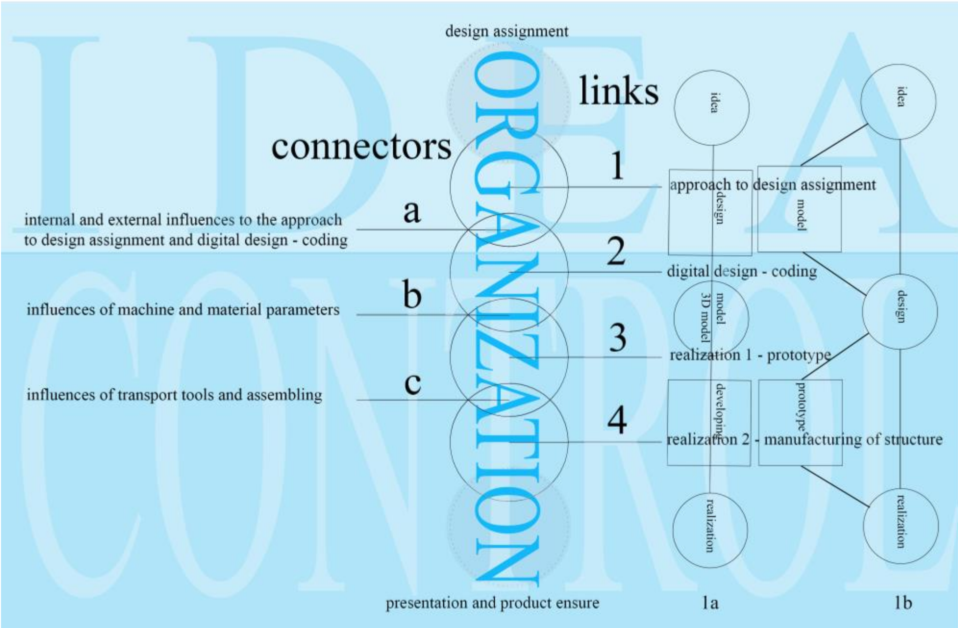

Fig. 1 Positioning of three dominant characteristics of the architect in the "digital chain" Scheme with elements of the "digital chain" *links* and *connectors* overlapping with 1a Conventional procedural model in design and realization in emerging architecture and 1b Digital procedural model in design and realization in emerging architecture

When discussing network intelligence, the reintegration of the architect into production, and how to approach the principle of "digital chain", "we might begin by noting that design is both a noun and a verb and can refer to either the end product or the process" (Lawson, 2004). Also, "design has been described as making inspired decisions with incomplete information" (Aish, 2005). The digital process provides an ideal balance to a continual architectural process. It embraces coding from idea through prototype to realization as a procedure that simultaneously enables creativity and control. Code allows for different levels of communication in the design process. It concurrently exists as the line, model, and the prototype, as well as concept, detailed design and architecture.

The design and realization parts within a "digital chain" are not separated, but overlap substantially as the fabrication inputs are included in the idea, both at the beginning of the chain and *link* 3 (realization 1 - prototype). In this way, the limitation of the architect's control over production is reduced. Parts of the conventional design are present throughout the chain, indicating that the machine influence is obtained directly at the idea stage. As a result, the idea and realization parts are much closer throughout the design process. The architect designs the process and returns to the realization in two ways. Indirectly, the architect knows the machine and material parameters needed to encode the idea. Directly, in terms of the architect's control over the products. "The focus is on the idea that the designer introduces to the program and on the possibility of expressing those ideas by using the idea of the program development" (Peters, 2013).

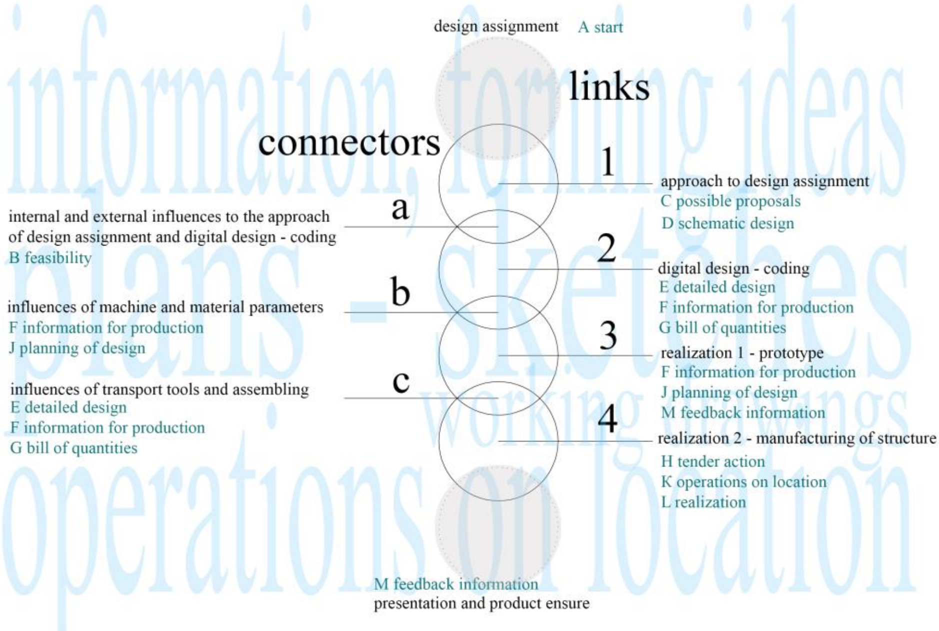

Fig. 2 Overlap of "digital chain" and Lawson's parts of the design

3. Architect in Digital Approach to the Process of Design and Realization in Architecture

Recent research, some of which is mentioned below, opens a scientific field that studies the influence of the digital approach on architecture. It pursues the positioning of the architect's activities and the characteristics of the architect's role in the architectural design and realization guided by digital principles. Today and in the future, the position of the architect in the design process based on the digital approach is to develop innovative, demanding, and thoughtful spatial solutions, regardless of the degree of overlap with conventional principles and activities.

Substantial changes have been observed as a result of the consideration of the "digital chain" principle in the architectural design and realization. Changes are also reflected in the design thinking among architects who have gone through an experimental process and who have pointed out to the overlap with the conventional chain as a necessary characteristic of the processes. Observing the overlap of key point positions and the relationship between the architect, machines and materials with parts of a "digital chain" sets up the current positioning of the architect options in the new approach. It is established as the architect's characteristics and activities and as a condition for continuity of principle. In conclusion, the dual nature of the architect's necessity is represented in the "digital chain" principle as the functionality of the process and the singularity of the architect's personality. The "digital chain" becomes the conductor of the architect's cognitive activity. Although with a proven linearity, implementing a complex idea requires the architect to connect several process chains. In short, it is fabrication through prototype analysis.

The pivotal responsibility, thus, lies with the architect to engage with digital design thinking and expand the instrumental knowledge of the machine to become an "expert amateur" (Paulos, 2013) who tinkers and hacks both conventional and new architectural design and realization processes. In this way, the architect explores, exposes, encapsulates, and engages context in these processes to derive spatial responses with an effect, a pre-personal, unmediated intensity that generates multiple meanings, thoughts, and emotions (Moussavi, López, 2009) yet expresses relatedness (Miodragovic, 2019).

Architects establishing the characteristics of architectural activities and the regulated positions of a "digital chain" will accelerate the meaningful application of technology in architecture. It will, thus, improve the design and production methodology as it is based on trust and architects' confidence in technological innovation.

3.1. Continuity of the process and constant change

Herbert Simon explains the essential characteristics of the designer personification: "Anyone, who invents the courses for acting of action to change the existing situations into desirable, is designing" (Simon, 1996). Simon's statement opposes the prevailing understanding of design as an answer to the question. Instead, it shifts the focus to the person who determines courses of action and whose desirable situation is designed. It, thus, resonates with the question of the architect's decisions in contemporary architecture and what knowledge, besides broad and multidisciplinary, is required.

Necessary effective solutions to the complex context, issue and architectural nature coded through developed technological tools can only be achieved by one medium - the architect. The architect's idea and digital skills fill the discontinuity of the process where product development is not digitally equivalent.

The position of the architect is the main parameter of continuity in the chain that ensures a coherent system. The architect's capabilities are necessary for the creative parts to survive as the vital link in the system.

The architect holds three parts of the control throughout the chain:

1. the verification of solutions between the rational and emotional conditions,
2. the certainty of the process's continuity,
3. the verification of the architect's necessity in the process.

The architect's connection, role and intention in the architectural design and realization are inseparable. The relationship is timeless and mutually dependent.

3.2. Machine in the architect's approach

Details are rarely present at the beginning of a conventional design process, partly due to the introduction of machinery. The role of the machine in creative professions is primarily automation. Although automation reduces and expedites activity, especially labour, it also reduces creativity. This is alarming for an architect unfamiliar with the digital process. The "digital chain" addresses the architect's activities with a machine in a changed position beyond sole automation to include the scope and meaning of the technological development. The strategic position of the architect requires interdisciplinarity, interactivity, and creativity to ensure the interplay between existing elements and programs and to establish flexibility in the controlled system. It also varies depending on the development of tools, design, and implementation. The architect, thus, becomes the designer of a machine tool “specific to every needed process” (Schodek, 2005).

3.3. Cooperative expertise and education

Technological change, as the trope of the contemporary context, requires a continuous expansion of expertise, learning, and knowledge exchange within architectural design and realization processes. Another significant factor is the power of influence grounded in the cooperation between stakeholders, conversations between colleagues, clients, customers, public administration, and others with vested interests in the architectural project. The unifying factor among them is the drawing, the main agency of codifying and communicating the architect’s idea. Therefore, the architect’s connection with the computer in every aspect is the improvement of both factors. As a result, the computer dictates the architect’s and architecture’s emerging position in business and in the design and realization process. In the future, an architect who does not engage with digital tools will be in the same position as an architect of the past who did not draw.

Lawson states that in architecture dealing with the “digital chain”, the problem and the solution are bound together, and the design process depends on the architect’s extension of knowledge implemented in the project. The concept formulation, the initial step of the design process, is derived from information gathered from briefing, analysis, synthesis, and evaluation. The subsequent design process steps are based on problem structuring, solutions, preliminary design, realization and details (Lawson, 2004).

Architectural activities are grounded in education, practice, and the link between theory and practice, and vice versa. The architect maintains the continuity of the digital approach as a fluid human-machine-material relationship. The creation and development of design expertise is the quality of each designer and the core thread of each architectural process (Markovic, Svetel, Lazovic, 2017).

This expertise is summarized in a seemingly small but essential part of the project - in the idea. The idea refers to the architect’s intuition and senses that bridge problems and solutions. For the architect, it is a tangible concept that visualizes the initial to the final moment of the process. It binds architectural thinking to drawings, which, as Denise Scott Brown says, “are never done as a piece of art, they are done as communication with self and with people around the table” (Lawson, Doorst, 2009). Ideas for architects always need further improvement, review and reinterpretation.

The first step in this process is related to the education of architects in terms of cognitive understanding of the technological part of the process - from the initial idea through digital design to the prototype realization and the finished product. It also extends to the process’s organization and control which contributes to the evaluation of the requirements of architecture as a discipline.

The overall consideration of architects’ involvement in architectural design and realization of the “digital chain” principle unveils several cognitive and perceptual aspects. They can be defined as art/emotion, logic/organization and prediction/continuity. These aspects accompany the architect’s abstract activities, such as vision, cooperation, talent, learning, and listening.

4. Trending Positioning of the Architect

The discussions in the previous sections present the positioning of an architect in architectural design and realization processes based on the "digital chain" principle. The experimental methodological framework, implemented through the subject impact testing, establishes the architect in relation to the key process points as criteria parameters: architecture, materials, and machines. Architect-machine, architect-material and architect-architecture relationships are allied, non-restrictive, and position the subject's tasks within the digital approach. The requirements of the architect's qualities and activities in the "digital chain" are observed based on digital techniques and the contemporary context. They require the recognition and necessary engagement of the digital architectural product, the duality (digital and conventional) of education and the design process, and the architect's experience of the contemporary digital architectural realm.

The paper recognizes the architectural influence in the digital approach to the architectural design and realization processes. Although the digital and conventional approaches to architecture are different and separate, they lack a clear boundary. The continuous approach in the architectural design and realization of the "digital chain" principle is both a challenge and a solution to the complexity of the contemporary context. The architect ensures this continuity as a conductive connecting fluid energy of all parts, links and connectors (Markovic, 2013).

The design and instrumental knowledge of digital technology are steadily spreading among architects. Its impact is felt mainly in large-scale architecture and material innovation and research. On the other hand, due to architecture's unwavering focus on the finished product, its design and realization do not use digital technology as a driving force for further development. Among other things, the *Fabricate 2014* conference laid the foundations for further digital architectural process development. After testing a large number of digital technologies in terms of the use of various constructive techniques, such as robotic fabrication and 3D printing in the service of architectural traditions through prototyping, pavilions and small buildings, the main topic is spreading to real architecture and complex processes and relationships of design and realization. As technological tools cause a change of sensibility and methods to influence the culture of design and construction, architects have to become experts in these areas, as they are needed to solve the problems of transforming a complex digital design model into a built reality (Gramazio, Kohler, Langeberg, 2014). During the closing session of *Fabricate 2024*, arguments were made for using digital technology for humane purposes, placing the architect at the forefront to pursue solutions to environmental problems and natural balance through digitally aligned, empathically guided processes.

The necessary overlap of the digital and conventional approaches is evident in the theoretical discourse and research of the digital approach to architecture. The duality in architectural education and design is present in the thinking of leading theorists, researchers, and practitioners, like Fabio Gramazio & Matthias Kohler (Fabricate, 2014), Mark Burry (Scripting culture, 2011), Mario Carpo (Digital turn in architecture 1992-2012), Robert Aish (Inside smart geometries, Fabricate, 2014) and Anchim Menges (Fabricate, 2014). The overview of their discourse and research can be summarized as a set of guiding principles:

- the digital approach and engagement of the "digital chain" principle overlap with the conventional principle. The differences are in the control of the process and the level of influence of idea realization;
- the architect dictates creativity and process control;

- the architect’s participation in the realization process is twofold: firstly, to determine the machine parameters and then to guide the interdisciplinary process as the application creator;
- the digital coding is a set of parameters that defines the new context;
- the architect ensures the digital approach continuity and the “digital chain” principle.

Architectural education demands a dual approach from the very beginning. First, it should demystify both traditional/manual/analog and digital methodologies, bridging the gap between the two. Additionally, it must integrate both theoretical and practice-based design, ensuring that design processes are firmly grounded in hand- and mind-drawing, model-making, and conceptual thinking while remaining open to future technologies, tools, and techniques. Architectural research topics should explore context-specific and personal characteristics through diverse approaches, highlighting the importance of varied outcomes and the development of future architectural profiles. This exploration moderates the establishment of conceptual frameworks, translating these characteristics into visual representations that deepen spatial understanding. In this sense, the contribution of technology is much more about the intention of the project and the process, which is more important than the tools (Burry, 2011).

The aim is to determine the criteria for the complexity of design and realization of emerging architecture as the reason and basis for directing the development, advancement and improvement of the architectural profession and the education of future *digitally born* architects (Palfrey, Gasser, 2008). It also determines the necessary qualities of the architect and tasks within the “digital chain”.

As transiency, indeterminacy, and instability become contemporary tropes, the digital approach becomes increasingly relevant for contemporary architecture (Miodragovic 2023). Its experimental approach to architectural thinking and working methods provides a valid methodology that establishes the positioning of the architect. It addresses the architect’s behavior in the digital approach regarding innovation, knowledge exchange, experience, and overlays, as well as challenges with the conventional approach (Miodragovic Vella, Markovic, 2024). The experimental approach combines the architect’s experience with iterative testing and investigations using prototypes to address problem formulation, provide proof of hypothesis and derive valid conclusions.

The architect’s activities are human drivers as 'soft skills' that determine the energy of the architectural design and realization processes of the “digital chain”, like intuition, instinct, emotion, intention, choice, decision, control, organization, coordination, creativity, flexibility, communication, expertise and education The activities, and/in relation to digital skills, based on spatial cognition in digital data/code driven processes in architecture also ensure the chain’s continuity, efficiency and agency in creating emerging architecture and are the parametric criteria for the possible future algorithmic relationships in the “digital chain”.

The accelerated shifts in the contemporary context impinge upon architecture (Cuff, 2012). For the architectural profession to develop and remain relevant, the role of the architect is to ensure things happen and to support others in making things happen. In the digital era, the architect is the project leader of the architectural project (Negroponte, 1995) that addresses and responds to these shifts by embracing new technologies and collaborative work processes (Carpo, 2023).

The emphasis remains on the importance of creativity, depth of personal characteristics, and freedom (Doshi and Hauser, 2024). These soft skills as (and) non-coding elements are crucial for addressing aspects of design that resist data(fication) within the implementation of the data-driven architecture. Alongside the development of digital fabrication (new machines and materials), these qualities continue to be primary drivers of future research.

5. CONCLUSION

Technology is the active agent that moves the culture and society after the causal principle. The relationship between architecture and technology entails the architects' trust and confidence in technological innovation and the acceptance of digital culture as progress, in which the user enables the direct role in designing. The possibility of practical applications of the "digital chain", in architectural design and realization represents, with the architect's influence and control at all steps, the basis for determining the continual digital approaches' qualities. They consist of properly assimilating production parameters within digital design techniques, i.e. the design of the necessary information (Svetel, 2022).

Today, we are faced with the unresolved position of the architect in the contemporary condition of architectural design and realization, instigated by a lack of proficient engagement of technology. The situation expands to include both the future positioning of the architect and the return to the primordial role of the designer who creates and builds. The paper considers the redefinition of architectural processes based on a digital approach of the "digital chain" principle. It does not dismiss the conventional approaches that retain their specific place, albeit with a changed meaning. The paper establishes the discourse of technological process, in which the architect's role is indispensable for the continuity of the process due to its primeval quality of unique observation of the product.

The positioning of the architect in the newer circumstances of the complex relationship of architecture and technology and the practical application of the "digital chain" process approach each new project as an experiment in architecture and construction. The result is unexpected outcomes and incomplete technological explorations.

The open-ended research focuses on the connection between digital design and realization as a translation of code from the design to the machine. It also includes the architect creating new and improving existing applications, as well as producing their digital tools. The network of research results is linked to the network of natural intelligence, as the beginning of the story on the amount of energy in the artificial environment contributes to the contemporary practice to uncritically develop relationships between architecture and technology. It is opening topics, such as:

- the positioning of architect in the digital age,
- the transition of approach to architecture - design and realization,
- design and realization based on data-driven, artificial intelligence and digital literacy,
- sustainability and resilience criteria with the integrity and life of structure - flexibility and emotions of the architectural space.

The paper provides the base for the approach to the problem of non-standard education and training of future architects in the technological realm and in the context of emerging architecture. It argues that introducing new digital tools is inevitable and entirely expected for today's, and especially for tomorrow's generations, born within the digital realm, but with a critical attitude. This generation's acceptance and knowledge of technology will be part of their personality. Architecture is showcase of the society. It moves boundaries by developing and improving architectural approaches, principles and relations, that will form the future architects. The positioning of the architect in emerging architecture today and in future is showing further impacts of technology on architecture.

The paper emphasizes the specialty and future importance of the personal creative features of the architect and their relation to the spatial atmosphere/ appearance with functional program and material tasks, as well as the freedom in the creation, recognizing it as a non-coding element in the coded (data-driven) digital processes. The study of human drivers is necessary for the future of architecture as a professional/practical and scientific discipline. In particular, it is relevant to the inevitable position of the architect-designer-artist in aesthetic, functional and formal terms in architectural design and realization within the framework of spatial cognition and the digital architectural world.

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REFERENCES

1. A.R. Doshi and O.P. Hauser, Generative AI enhances individual creativity but reduces the collective diversity of novel content, Science Advances, 2024, Vol 10, Issue 28, doi: 10.1126/sciadv.adn5290
2. A.Picon, The materiality of architecture, Minneapolis:University of Minnesota press, 2020.
3. Sakshi, A.Maruna, A.K. Sharma, Blockchain-based digital chain of custody multimedia evidence preservation framework for internet-of-things, Journal of Information Security and Applications, Elsevier, Volume 77, September 2023, doi.org/10.1016/j.jisa.2023.103579
4. A. Witt, A machine epistemology in architecture Translated By Annette Wiethuchter. Candide-Journal For Architectural Knowledge, 2010.
5. B. Colomina, and M.Wigley, Are we Human? Netherlands: Lars Mueller Publishers, 2016/2022.
6. B. Lawson, How designer think, New York: Routledge, 2005.
7. B. Lawson, What designers know, Oxford: Architectural press, 2004.
8. B. Lawson and K. Dorst, Design Expertise, New York: Routledge, 2009.
9. B. Peters, T. Peters, Inside smartgeometry - Expanding the Architectural Possibilities of Computational Design, Chichester: Wiley, 2013.
10. D. Schodek, M. Betchthold, K. Griggs, M.K.Kao, M. Steinberg, Digital design and manufacturing, Hoboken: Wiley, 2005.
11. D. Cuff, Introduction: Architecture's Double-Bind. The Sage Handbook of Architectural Theory, 2012, pp. 385-393.
12. E. Paulos, The Rise of the Expert Amateur: DIY Culture and the Evolution of Computer Science, ASPLOS'13 Proceedings of the eighteenth international conference on Architectural support for programming languages and operating systems, 2013, pp. 153-154.
13. F. Gramazio, M. Kohler, S. Langenberg, ed., Fabricate, ETH Zuerich: gta Verlag, 2014.
14. F. Moussavi, and D. Lopez, The function of form. Actar, 2009.
15. G. Vrachliotis, On New Technological Condition, Birkhaeuser, 2022.
16. H. Simon, The science of artificial, Cambridge: MIT press, 1996.
17. I. Miodragovic Vella, Markovic, S., Topological Interlocking Assembly: Introduction to Computational Architecture, Appl. Sci. 2024, 14(15), 6409; https://doi.org/10.3390/app14156409
18. I. Miodragovic Vella, Digital design in 'peripheral'contexts, Volume 1 - Digital Design Reconsidered - eCAADe 41, 2023, pp.61-68.
19. I. Miodragovic Vella, A stereotomic approach to regional digital architecture University of Malta, 2019.
20. I. Svetel, Information in Architecture in the Digital Age, Conference: On Architecture Philosophy of Architecture, 2022.
21. K. Subrin, S. Garnier, T. Bressac, B. Furet, Digital chain development for sanding application with a kinematically redundant robotic system, Procedia CIRP Volume 82, 2019, pp.515-520, https://doi.org/10.1016/j.procir.2019.04.063

22. L. Mangliar, M.Hudert, Enabling circularity in building construction: Experiments with robotically assembled interlocking structures, Structures and Architecture A Viable Urban Perspective?, 2022, pp. 585-592
23. L. Hovestadt, On Digital Architecture, Volume I, II, Books I-III, Books, IV-VI. ETH Zuerich: Birkhaeuser, 2023.
24. L. Hovestadt, Catalog of Special exhibition of CAAD Chair, ETH Zuerich. Basel:Swissbau-Basel, 2005.
25. M. Burry, Scripting Cultures - Architectural Design and Programming. AD Architectural Design, Chichester, UK: John Wiley and Sons, 2011.
26. M. Carpo, 2023. "A short but believable history of the digital turn in architecture." Accessed Mai 3, 2024. https://www.e-flux.com/architecture/chronograms/528659/a-short-but-believable-history-of-the-digital-turn-in-architecture/
27. M. Carpo, The Digital Turn in Architecture 1992-2012. Chichester, UK: John Wiley & Sons, 2012.
28. M. Carpo, The alphabet and the algorithm. MIT Press, 2011.
29. M.L. Chiu The jump of digital design thinking Ecaade 2006
30. M. Cvetić, S. Marković, Experience and theory in architectural design: Digital chain case, AM: Journal of art and media studies, No. 12/2017, theme: Architecture with(in) art and theory, Faculty of Media and Communication, Belgrade: Singidunum University and Orion art (2017): 121-134
31. M. Numfu, A. Riel, F. Noël, Virtual reality based digital chain for creating a knowledge base of hand gestures in maintenance tasks, Procedia CIRP, Volume 90, 2020, Pages 648-653, https://doi.org/10.1016/j.procir.2020.01.122
32. N. Cross, Design Thinking: Understanding How Designers Think and Work, 2nd edition, London: Bloomsbury Publishing, 2023.
33. N. Cross, Designerly Ways of Knowing, Basel-Boston-Berlin: Birkhaeuser, 2006.
34. N. Negroponte, Being Digital. London: Hodder and Stoughton, 1995.
35. O. Meski, F. Belkadi, F. Laroche, B. Furet, Towards a knowledge-based framework for digital chain monitoring within the industry 4.0 paradigm, Procedia CIRP Volume 84, 2019, Pages 118-123, https://doi.org/10.1016/j.procir.2019.04.250
36. P. Dohmen, K. Rüdenauer, ETH Zürich Institute for CAAD. Professor Dr. Ludger Hovestadt, Digital Chains in Modern Architecture, eCAADe 25, 2006, pp. 801-804
37. R. Aish, From intuition to precision, AA Files, No.52, Architectural Association, 2005, pp. 62.
38. R.A. Loveridge, Process Bifurcation and the Digital Chain in Architecture, PhD dissertation, EPFL, 2012.
39. veridge, Process Bifurcation and the Digital Chain in Architecture, PhD dissertation, EPFL, 2012.
40. S. Markovic, Size in the process of design and realization in emerging architecture – the Digital Chain approach, SAJ, Faculty of Architecture University of Belgrade, Vol 12, No1, 2020, pp.21-35.
41. S. Markovic. Integrity and Life in process of design and realization in emerging architecture – Digital Chain case, Structural Integrity and Life Vol. 20, No 1 (2020): 3–10.
42. S. Markovic, Svetel I. and Z. Lazović, Redefinition of the process of design and realization in emerging architecture on the principle of "digital chain", Facta Universitatis – series architecture and civil engineering, 2017. 15(3): 295-306.
43. S. Markovic, "Positioning of and architect in the process of design and realization of architecture based on a principle of a "digital chain", PhD dissertation (in Serbian, in procedure), University in Belgrade, 2016.
44. S. Markovic, The guide through the process of "digital chain" in architecture (bilingual: Serbian/ English), Endowment Andrejević, Belgrade, 2013.
45. S. Markovic, and A. Nikezic, Revising the Position and Scope of *Being Digital* in Architectural Design, 2024. in publication procedure
46. V. Miller, Understanding digital culture, London: Sage publications, 2011.

KONCEPT POZICIONIRANJA ARHITEKTE U KONTINUALNOM DIGITALNOM PRISTUPU PROJEKTOVANJU ARHITEKTURE – PRINCIP "DIGITALNOG LANCA"

Proučavanje razvoja digitalne tehnologije u arhitekturi tokom poslednjih trideset godina daje jasniju sliku mogućnosti istraživanja procesa pozicioniranja arhitekte u arhitektonskom pristupu zasnovanom na kontinualnom projektovanju i realizaciji vođenim digitalnim podacima (engl.

digital data driven design) na primeru principa „digitalnog lanca“. Digitalni alati i procesi su se razvijali prateći tehnološki napredak i podržavajući arhitektonsko projektovanje, ali izazivajući uticaj i ulogu arhitekte projektanta.

U skladu sa tim, pozicioniranje arhitekte u projektovanju i realizaciji arhitekture je proces koji se neprestano razvija, evoluira, napreduje i menja, ali ne istovremeno sa razvojem tehnologije. Rad ovo istražuje sa fokusom na „digitalnom lancu“, koji je kontinualni pristup koji povezuje arhitektonsko projektovanje i realizaciju kodiranjem procesa i uključuivanjem digitalne fabrikacije (mašine i materijala) i arhitekte u svaki korak stvaranja arhitekture.

Metodološki, ovo istraživanje se zasniva na preklapanju informacija (brzog) pregleda principa kontinualnog projektovanja vođenog digitalnim podacima (primer „digitalnog lanca“) tokom vremena i konvencionalnog (analognog) projektovanja usredsređenih na diskurs, ulogu i uticaj arhitekte u sadašnjem i budućem projektovanju i ostvarenju arhitekture. U radu se ne definiše tačna pozicija arhitekte u „digitalnom lancu“ jer se proces i dalje razvija i zavisi i od vrste fabrikacije, uzimajući u obzir i slobodu izbora arhitekte. Međutim, rad identifikuje zone i vrste uticaja ovih procesnih efekata na arhitektu, i određuje neophodnost i ulogu arhitekte kao projektanta u tom procesu.

Ovaj rad je usmeren na postavku konceptualnog okvira pozicioniranja arhitekte koji se trenutno razvija, dok bi precizno definisanje pozicije sprečilo arhitektu u sopstvenom izrazu kreativnosti. Međutim, novi istraživački pravci otvaraju naučno polje stalnog redefinisanja procesa projektovanja sa arhitektonskim uticajem u pogledu aktivnosti i karakteristika uloge arhitekte u digitalnim pristupima projektovanju i realizaciji arhitekture.

Ključne reči: *novonastajuća arhitektura (engl. emerging architecture), pozicioniranje arhitekte kao projektanta, redefinicija procesa projektovanja, kontinualno projektovanje zasnovano na podacima (engl. data driven design)*

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REGENERATION OF RURAL ARCHITECTURAL HERITAGE: CASE STUDY OF FIVE TRADITIONAL HOUSES IN SIRINIĆKA ŽUPA

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Abstract. *The architectural legacy of Sirinićka Župa, located in the south part of the Republic of Serbia, at the foot of the Šar mountain, is best known by traditional houses. The uniqueness of the style of old Sirinić houses is attributed to the use of local materials and adaptation to local topography, climate and the morphology of settlements.*
The study recognizes the importance of preserving the authenticity of the residential architectural heritage of Sirinićka Župa and highlights the need to understand the potential of these buildings in order to determine future appropriate interventions More specifically, the research analyses the development of traditional residential architecture in Sirinićka Župa area, focusing on five characteristic and representative house examples – their original design concept and value, present state, and the regeneration direction. Results contribute to the existing body of literature by providing a detailed scientific description of the values of Sirinić houses, as well as the justified regeneration-related interventions derived from delicate approach and impact assessment.

Key words: *traditional houses, Sirinićka Župa, regeneration, sustainable rural development*

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1. INTRODUCTION

Over the past few decades, the concept of sustainable development has become increasingly prominent in both scientific and practical contexts. Sustainable development includes three aspects: economic, environmental and social sustainability. In the practical application of sustainability principles in residential architecture in Serbia, the focus is still mainly on the first two elements, while the latter is the least studied and represented. From the architectural aspect, sustainability is reflected in the efficiency of residential structures, observed through all key life cycle phases: construction, exploitation, and renovation or reconstruction [1]. For a successful and sustainable regeneration of architectural heritage, all three elements of sustainability must be met, which is a big challenge due to the complexity of the heritage restoration process. For example, one of the main components of architectural sustainability is reflected in the adaptability of the housing space itself, that is, its ability to meet the complex housing needs of different types of users and provide opportunities for multiple uses [1]. Through design intervention, the architect's leading question is: how to establish a fair correlation between contemporary needs and traditional local culture [2]?

Around the world, there are numerous examples of interventions undertaken within the process of regeneration of traditional family houses and other rural architectural structures. The specificity and the scope of these actions depend on several factors, such as the current state of a building being regenerated, its architectural heritage value, the prescribed measures and degree of protection, modern architectural trends and the demands of future users. Furthermore, cultural heritage includes built structures that have significant cultural, emotional, temporal, historical and economic value to the community. This intrinsic value is a key attribute that positions heritage objects as catalysts for the development of settlements. Apart from their importance to the community, the design of heritage structures and their capacity to attract new ventures are equally important [3].

The traditional (folk) architectural culture was gradually assimilated in the wave of urbanization and the rural regional culture was eroded to varying degrees, mainly manifested in the absence of cultural continuity and environmental protection [4].

At the beginning of the last century, and even earlier, numerous residential buildings were built. However, due to many factors, the importance and the value of these structures became less important. As a result, it has been imperative to undertake efforts to restore these structures [5]. Traditional architecture offers lessons that are the basis for environmentally responsible architecture and the principles of ecologically sustainable development. Traditional architecture as a regional language of architecture, based on the idea of preserving the local and regional uniqueness of architecture, is a powerful inspiration and catalyst for future realizations [6]. During the regeneration of traditional houses, sociological, economic and physical aspects should be taken into account in order to preserve the identity of the place where the houses are located and to continue the transmission of cultural values and heritage to future generations. Applied vernacular building cultures respected the landscape through the visual aspect of available local materials, the shape and size of the building, its decorative details and its relationship with the environment, showing man's ability to adapt to the place and to satisfy his needs [7]. Therefore, with the aim of sustainable development of Sirinićka Župa, it is necessary to pay equal attention to the preservation of its natural, architectural and cultural heritage. This requires careful planning and construction practice. Regeneration is a challenging process that requires knowledge of cultural specifics, understanding of the characteristics of inherited physical structures and recognition of the possibility of adequate use of architectural objects after implemented interventions [8]. Traditional architectural objects contribute to the preservation of not only material, but also immaterial values of the community and thus provide support for its continuity and continuous development [9]. Therefore, the conservation and regeneration of architectural heritage requires a better understanding of authenticity, instead of limiting it to the preservation of the original appearance and structures. Preserving the intangible aspects of construction techniques and functional way of life in traditional architectural heritage is valuable [10].

2. TRADITIONAL SIRINIĆ HOUSE

Throughout history, the architectural styles of different communities have been defined by their unique characteristics including language, clothing, customs and folklore. These characteristics influenced the materials, technology and environment used by each community, resulting in recognizable local forms and details in their architecture. However, the collapse of cultural boundaries in the twentieth century led to the homogenization of architectural styles, erasing some of these distinctive features [11].

The creation of settlements in the region of Sredačka, Sirinić and Goranska Župa should be viewed in connection with the entire Šar mountain, Kosovo and Metohija, as well as the southern Balkans, where these areas are located in this region. They are located in the southern part of the country, near the northeastern part of the mountain Šara.

The research area is located in the extreme south of the Republic of Serbia, on the northeastern slope of the Šar mountain, encompassing the flowing waters of the Lepenac River, stretches the region known as Sirinićka Župa. It is historical significance dates back to the 13th century when it was first mentioned in the "Serbian Gospel" document. The 1322 "Charter of King Dušan" further solidifies its importance as it describes Sirinić as a parish belonging to the renowned Hilandar monastery. Subsequent Ottoman records make mention of the villages within Sirinić using linguistic forms that closely resemble their present-day names.

We follow the development of settlements in these Šar parishes from its beginnings in this part of our country since the Neolithic, through the ancient and early Christian periods, the Middle Ages and up to our days. Traces of Pelasgian, Illyrian, Thracian, and in some parts Hellenic, Roman, Slavic and Turkish-Oriental influence and ethnic presence are visible in these parishes [12]. As for the analysis of the traditional Sirinić house, which belongs to the style of the Balkan houses, there are divided opinions. Turkish scholars claim that Balkan houses bear a significant resemblance to homes inspired by the Ottoman Empire, while the Balkan peoples themselves remain true to the unique origins of their homes [13]. Balkan researchers focus on the spatial organization of traditional homes, often referring to Byzantine architecture. Pointing to the oriental influence in Byzantine architecture, it is recognized that the environment was closely connected with Asia Minor and susceptible to external influences from that direction. However, it is also noted that this environment was rich in diverse cultural elements. The houses of the Balkans and the Eastern Mediterranean were developed within the program content of the Byzantine houses, which themselves were a synthesis of Greek, Roman and Asia Minor houses. After the Byzantine palaces, the medieval feudal towers represented the next stage in the development of Balkan houses, with multi-story stone towers for defense and housing [14]. Residential architecture of the 16th and 17th centuries in Serbia is not new, but an extension of general Byzantine, Slavic and Middle Eastern concepts. Lively activity on the construction of rural villages appeared only in the second half of the 18th century [14]. That was the time of the real renewal, so that a greater number of villages got their final rural structure at that time, which we know today in Šarplanina villages [15]. After a period when wood was mainly used as a material - mostly during the rule of the Turks, there was a more intensive construction of stone houses. After liberation from Turkish rule in 1912, this type of house began to dominate the entire area of the Sirinićka Župa. The walls of houses are usually made of stone, which is known as the oldest natural building material and the most durable if properly installed. The "weaker" side of the stone wall is wider than the long material wall. Local builders were real virtuosos when building the building from crushed stone. The work of these unknown "domestic" craftsmen was usually masonry walls made of quarry stone, without using any binding material. They called this type of construction "dry" construction, "dry stones". On the territory of Serbia, depending on geographical and climatic conditions, availability of building materials, we distinguish three major types of buildings. "Bondučarske kuće" are characteristic for the southern, eastern and central parts of Serbia, generally for those regions that are poor in construction wood. "Brvnara" is typical for mountainous, wooded areas of the country, primarily western Serbia. In the north of the country, the dominant type of house was a house made of wood, or a house built with "ćerpić", and given the lack of other types of building materials [16].

The architecture of folk structures in Sirinićika Župa exhibits a distinct consistency, particularly in the variations of the longitudinal čardak and ajat. These forms can be further simplified to their subvariations, such as corner porches and central porches, or porches on the first floor [17].

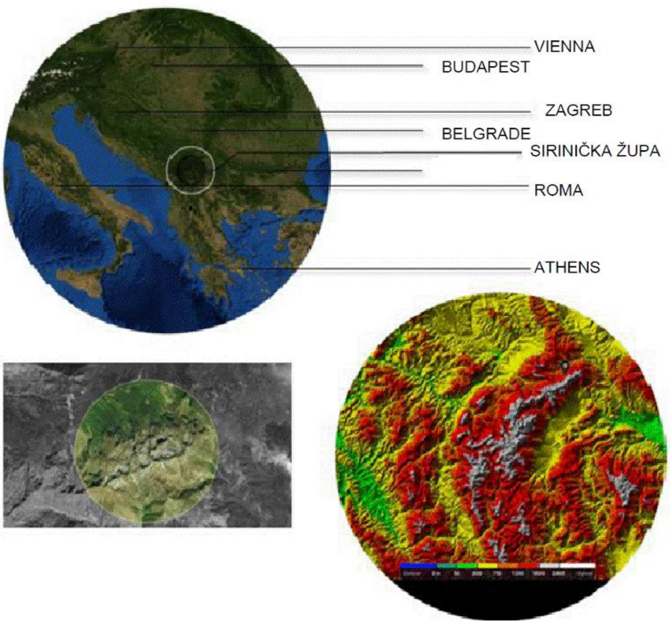


Fig. 1. The geographical position of the Sirinićka Župa in Balkan Peninsula

The area of Sirinićka Župa is known for its abundance of well-preserved traditional houses, providing valuable insight into the region's history and culture. After conducting a field research, five traditional houses from the late 19th and early 20th centuries were identified and chosen to represent the region. In order to be considered for regeneration, the selected houses had to meet certain criteria. First, they had to be representative of the traditional architecture in the area. Second, they had to be built during the time when traditional architecture was at its peak. Third, the houses had to be situated in accessible areas with tourism potential. By carefully selecting houses that met these criteria, the regeneration process would make a significant contribution towards preserving the traditional architecture of the region. The examples of analyzed traditional houses belong to Serbian families, that can be proven by surnames of families who own them.

3.1. House of the Stanišić family

The house of the Stanišić family is located in the village of Sušiće, about eight kilometers north of the municipal center - Štrpce. It was built between 1871 and 1875 According to the type, the house of the Stanišić family belongs to the old Kosovan ground floor with details specific to Sirinićka Župa. The house is characterized by a good disposition in relation to the immediate natural and built environment. The length of the base is 15.50m x 6.60 m. The basic structure consists of massive surrounding stone walls built in the shape of the Cyrillic letter "П", which is the same in other Sirinić houses. The front facade wall of the house is recessed in relation to the sides so that it forms a porch - "čardak". The location of the house on a plot on a sloping ground made it possible to create a basement space, which is accessed separately from the side. The basement was used to keep livestock. From the part of the čardak, you can access three domestic rooms: the main room with a fireplace and two side rooms that were mainly used as sleeping areas. The walls were built with stone from the maidan near the building. The interior of the walls is lined with a mixture of mud and clay. The ceiling construction was made of wood. It was made by placing the attic beams in parallel and resting on one side on the end beam of the brick wall and, on the other side, on the end of the stone wall. Between the attics "kolenci" were placed, i.e. battens wrapped in a bundle of rye straw or hay, which was glued and rolled in mud before being incorporated into the structure of the mezzanine structure, which ensured better thermal insulation. The roof is gable, with a gentle slope of around 25 degrees and dropped eaves around 50 cm wide. The roof covering was made of regularly arranged stone slabs with overlaps, made on site. The roof structure is simple, made by placing rafter supports over the ceiling beams. The load on the roof is evenly distributed. The main facade of the house of the Stanišić family with its accentuated čardak and transverse beams provides a motif that defines the identity of the house and a recognizable architectural expression of the traditional architecture of the Sirinićka Župa.

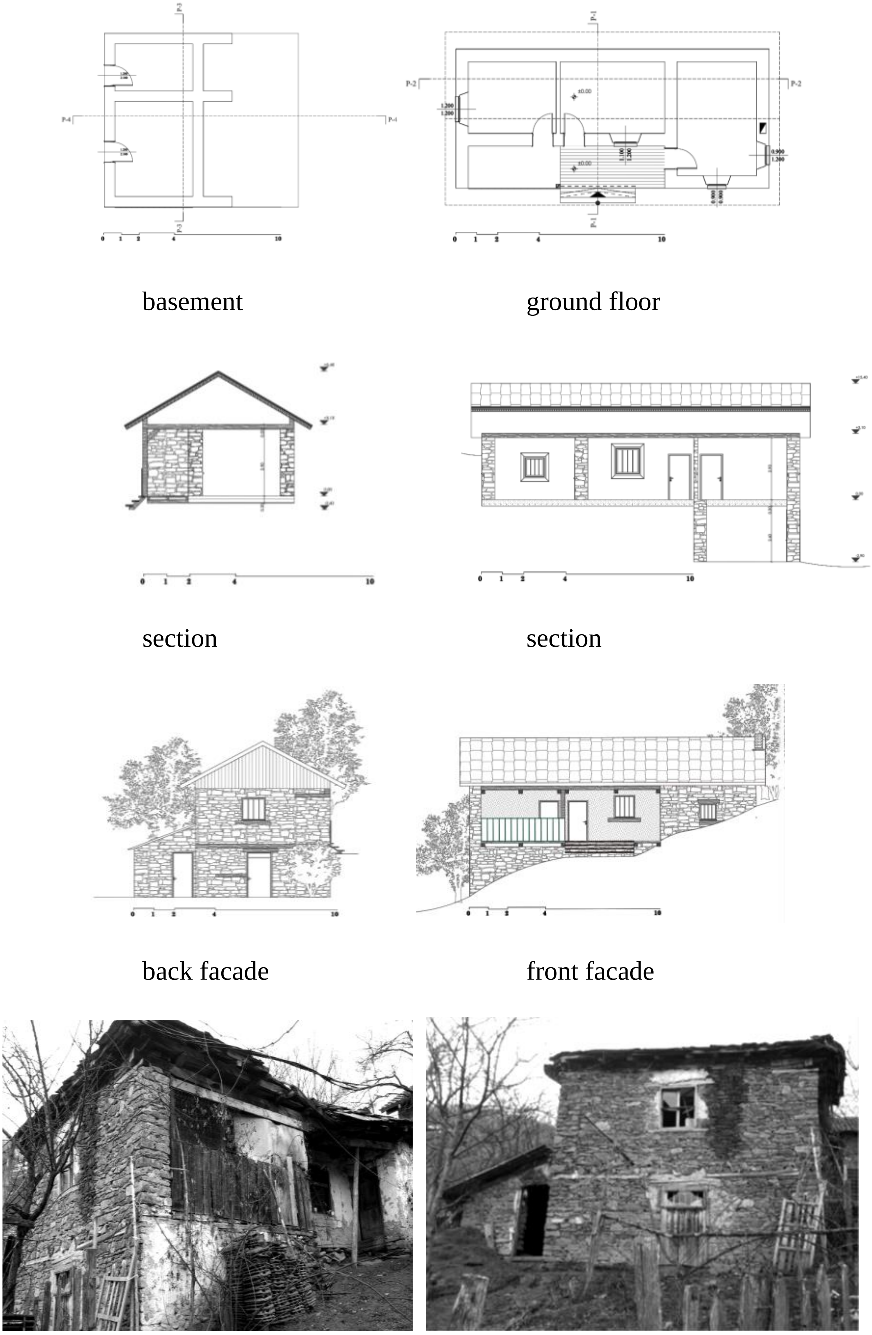


Fig. 2 House of the Stanišić family

3.2. House of the Nikolčević family

The house of the Nikolčević family is located in Štrpce, near the church of St. Nicholas. It was built at the very beginning of the 20th century, in 1901. Unlike other houses built in the same period, the house of the Nikolčević family is quite well preserved. The house is positioned on the side border of the plot, while the main yard is next to the public road through the hamlet. The dimensions of the base of the house are 18 x 7 meters. The main facade is oriented towards the south. At the same time, the southern facade is the most open, while the opposite - northern - is closed. The shape, orientation and position on the steep terrain are such that all rooms are well-sunlit in the winter when the sun is low, and during the summer, thanks to the existing canopy, they are protected from direct overheating. The space of the house is vertically organized through two floors - the basement part, which extends along the length of almost half of the house, and the four-part residential floor. The main room is the most prominent, with a side room next to it, i.e. an auxiliary room and two bedrooms. Each of the four rooms is accessed from the common area - covered porch on first floor - "ajat ". At the base of the house, an elongated rectangular čardak occupies a central place. The dimensions of the ajat are 10 x 1.80 meters. This spatial-architectural element also plays a leading role in the design of the front facade, together with a simple wooden fence, associated wooden pillows and columns that are arranged in a regular rhythm. The outer stone walls (built with dry construction) are 60 cm thick, while the inner brick walls are 30 cm thick. The mezzanine construction is wooden with a light earth coating. The roof is hipped, with an inclination of about 3 degrees, covered with tiles that were made and baked near the building itself, "ćeramida". The walls are coated on both sides with smooth plaster made of clay, mud and straw. The ground floor is wooden. The basement part was intended for storage. The darkest part was used to store wine. The basement floor is made of rammed earth, and the inner walls are rough and rough. The room has only one window oriented to the northwest, while the entrance door is positioned on the southern, main facade.

3.3. House of the Nikolić family

The house of the Nikolić family is located in the village Gornja Bitinja, four kilometers northwest of Štrpce. It was built at the end of the 19th century, and its first owner and member of the then influential Sirinić community was named Erdan. Later, he sold the house to Stojko Nikolić, whose ownership it is even today. The main facade is oriented towards the southeast, which allows for good sunlight in the interior during the winter. The space of the house is organized vertically through two floors. The lower, ground floor is partially buried in the ground on the rear, northern side. Unlike the previous two examples (the house of the Stanišić family and the house of the Nikolčević family), the house of Nikolić is much simpler. The base is rectangular with dimensions of 12x6 meters. The ground floor is divided into two parts. The purpose of the smaller part was to keep livestock, while the other larger part was used by the household. The staircase is designed as an external one. On the first floor, it ends in a semi-open space of a small čardak dimensions - 5.8 x 2 meters. On the first floor, in addition to the čardak, there is also one room used for night rest, while all the remaining space is intended for storing food for livestock. All external walls are made of massive stone, and their thickness is 50-60 cm. The thickness of the inner walls ranges from 20-30 cm. It is only that the front facade wall on the first floor was formed as a bond arm. The front facade of the house is plastered with a mixture of mud and clay, while the other three are made of stone in combination with wooden details. The wooden fence of the conservatory is made of modestly hand-finished vertical boards. The roof of the house is classic, traditional, hipped, with a slope of 30 degrees. On the eastern side, the eaves are overhanging 110 cm, in relation to the plane of the facade wall, while on the other sides this overhang is 80 cm. The covering is made of ćeramida, made near the building.

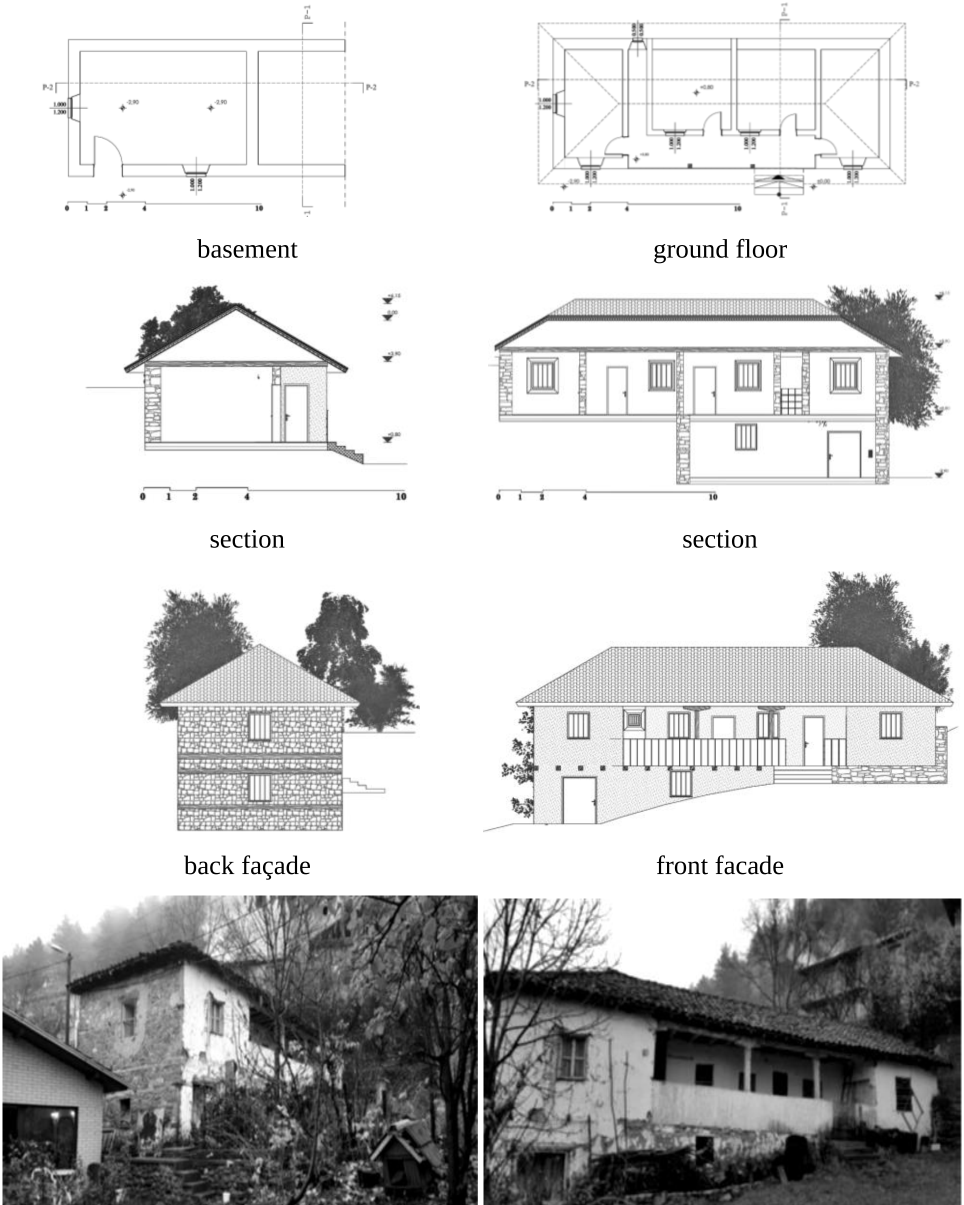
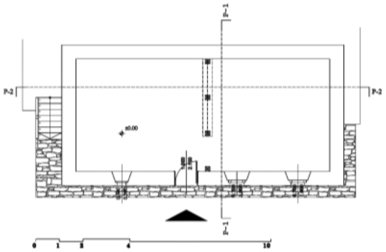
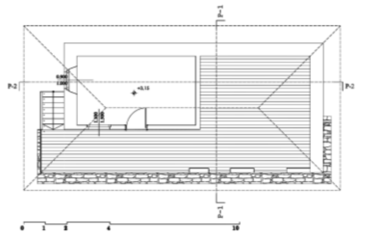


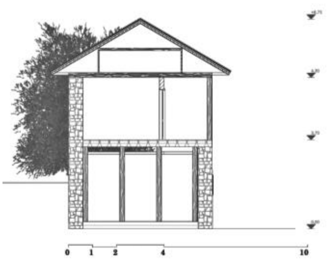
Fig. 3 The house of the Nikolčević family



ground floor

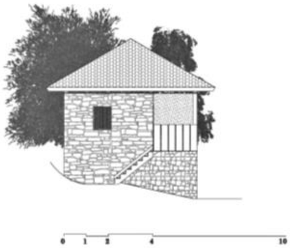


first floor

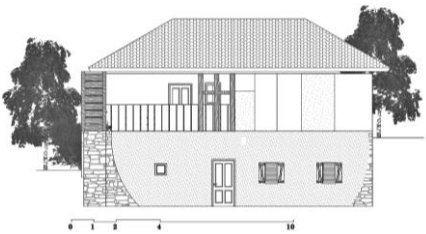


section

section



back façade



front facade

Fig. 4 The house of the Nikolić family

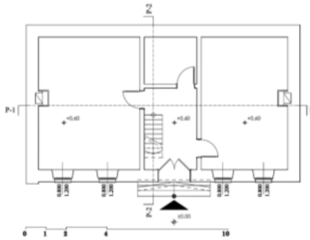
3.4. House of Mladenović-Kovačević family

The house of the Mladenović family is located in the village of Berevce, two kilometers north of the center of Štrpce. It was built by local craftsmen, in 1924. Compared to the other four houses, the house of the Mladenović-Kovačević family is functionally the most complex. The rectangular dimensions of 13.5 x 7.7 meters are repeated throughout the ground floor and first floor. It is interesting that the house of the Mladenović family does not have a front yard, but only the back, because it is placed on the regulation line. The area of the house is accessed directly from the street. The plot on which the house is located is sloping, so its rear side is buried in the ground. The entrance (front) facade is oriented towards the southeast. The organization of the space of this type of Sirinić house is determined by the plot itself. On the ground floor, there are four rooms that belong to the living-economic block. The main room is a room with a fireplace, followed by a storage room (in the buried part of the house), a work room that had the double function as a kitchen and a workshop and a corridor where the staircase, leading to the first floor, is located. There is a sleeping area on the first floor, which consists of five rooms. Each of these rooms is accessed from the čadrak" area. The čardak of the house of the Mladenović - Kovačević family has a complex base consisting of the main (wider) and two narrow side arms. In summer, the wider part of the veranda was used as a living area during the day and even as an open bedroom during warm summer nights. With its details in the processing of the wooden pillars and the fence, the veranda gives a striking expression to the entire house and emphasizes the unique combination of two traditional design variants (a more reduced form from the beginning of the 20th century and ornamental motifs of a slightly older date).

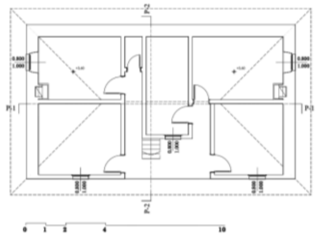
The outer walls are made of massive stone. Their thickness on the ground floor is 60 cm, and on the first floor is 20 cm. Partition walls are bonded, with adobe filling, which is also a good thermal insulator. The facade is covered with a mixture of mud and straw, and then coated with lime. The roof is hipped, formed at an angle of 30 degrees, with overhanging eaves up to 30 cm wide. The covering is a roof tile, ćeramida.

3.5. House of the Kecić family

The house of the Kecić family was built in 1913, in the center of the old part of Štrpce. It is considered to be one of the most beautiful examples of traditional residential architecture of Sirinićka Župa. Like most of the old Sirinić houses, the house of the Kecić family was built on a slope, which conditioned its spatial organization and form. The building has two floors. There are two rooms on the ground floor - the "kuća" and the "klećа", and, on the first floor, there is a living room, two bedrooms, a barn and a veranda, that stretches the entire length of the building. The connection between the two floors is achieved by an inclined ramp, which represents a unique solution in the context of traditional Sirinić architecture. In the living room, on the first floor, there is a built-in fireplace, and there are niches on its left and right sides. All ground and two-story external walls are made of crushed stone. Mud was used as a binder. The other walls are wooden bonded, with adobe filling. The mezzanine structural assembly (still preserved in its original form today) is made of wood. The roof has a slight slope, around 25 degrees, accentuated by a roof "badža" and dropped eaves, 80 cm wide.

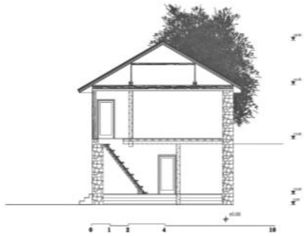


ground floor



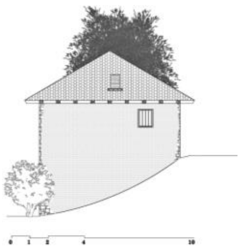
first floor

section



section

back façade



front facade

Fig. 5 House of the Mladenović - Kovačević family

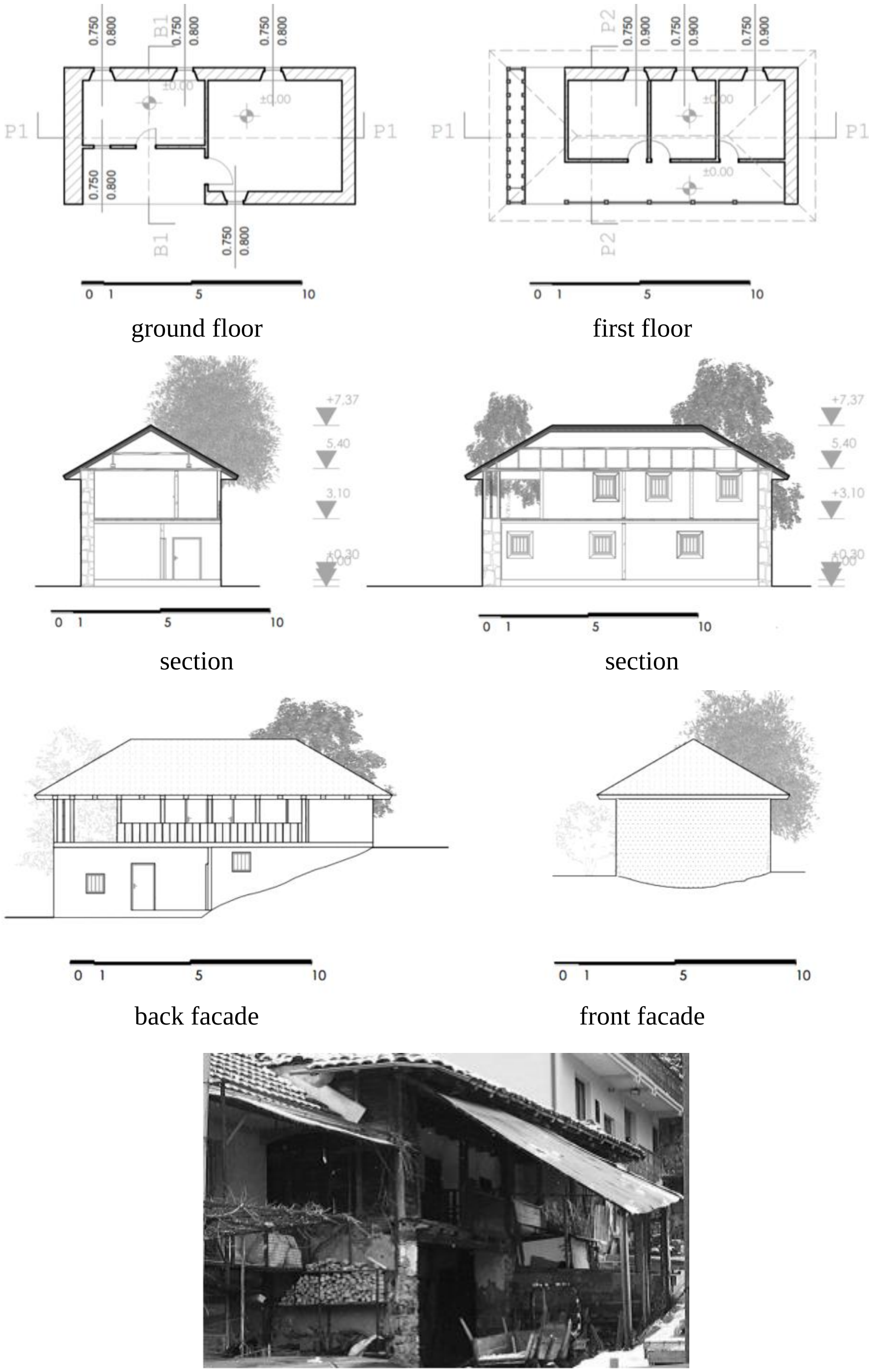


Fig. 6 House of the Kecić family

4. Architectural Regeneration of Traditional Houses: Characterization of Interventions

When it comes to creating or modifying physical structures, building design plays a fundamental role in reshaping the spatial environment to meet human needs, cultural influences, current demands and economic considerations [18]. The primary goal is to preserve the character and cultural significance of the building while incorporating functional elements that are in line with current trends, meeting human requirements [18].

Taking into account the current challenges that Sirinićka Župa is facing, the recommendations presented in the research paper are rooted in the aim of preserving the authenticity of the processed architectural heritage to the greatest extent possible. The following excerpt provides suggestions for the restoration of five detached houses. Three alternative approaches are proposed for each house:

1. interventions of minimal need,
2. medium-sized interventions,
3. radical solutions.

All selected instances have the following attributes in common:

- They are in a relatively satisfactory condition, suitable for restoration, whose priority is the preservation of the original characteristics,
- They were built in a similar period of time, either at the end of the 19th century or at the beginning of the 20th century,
- They exhibit a similar architectural style.

The minimally necessary proposed interventions for five studied traditional houses in Sirinićka Župa, refer to preservation of their primary function as permanent single-family dwellings. These interventions include:

- Repair of fences and reconstruction of access paths to houses;
- Performing static analysis to strengthen the basic structure of houses in accordance with modern standards;
- Introduction of modern water, sewage and electrical installations;
- Replacement of worn-out veranda components with the new ones, made of the same wooden material and identical design;
- Integration of an additional layer of environmentally friendly thermal insulation into the thermal envelope of the building, without changing its original appearance;
- Restoration of facades with originally used materials while adhering to the original aesthetics;
- Restoration of worn-out elements of the roof structure and its covering;
- Repair of window frames and doors and application of outer layers to improve insulation properties; and replacement of the final layers of materials in the interior space, in accordance with the original materials.

4.1. Proposal for the regeneration of the house of the Stanišić family

In addition to the most frequently mentioned interventions, the necessary measures for the restoration of the house of the Stanišić family in the village Sušiće would be the installation of a bathroom. In addition to that, special attention should be paid to the renovation of the roof, which is currently covered with stone slabs. It is essential to find a qualified manufacturer capable of producing and installing stone slabs that match the original quality and shape. It is planned to convert the house into a *Museum of Folk Heritage* of Sirinićka Župa. Each existing room will be repurposed as an exhibition space dedicated to a specific aspect of heritage. Within this plan, it is necessary to build a toilet for employees and visitors in the existing dimensions, preferably on the lower floor. Furthermore, the intended area with an internal glass partition should be allocated for an office and potentially a tourist information point. It is of crucial importance to preserve the authenticity of the building after the restoration, which implies the implementation of extensive conservation works.

The proposal for the regeneration of the house of the Stanišić family (Fig. 2), as a part of a **medium-sized** project, refers to its conversion into the Museum of Traditional Heritage of Sirinićka Župa. Each of the existing rooms would be converted into an exhibition space dedicated to a specific segment of the heritage. In this variant, it would be necessary to create a toilet for employees and visitors within the framework of the existing dimensions (preferably on the lower floor), as well as to separate a space with an internal glass partition that could have the function of an office and, optionally, a tourist point. The authenticity of the building after the intervention would have to remain at a high level, which means carrying out conservation works at a full scale.

The old house of the Stanišić family would retain its original purpose of individual housing after a **radical intervention** (which primarily integrates the mentioned minimum interventions). Changing the functional organization would mean removing the dividing walls between three rooms of smaller square footage, in order to get a more spacious living room with a kitchen area, a bedroom and a new bathroom. In this variant, the dimensions of the window openings would be increased or new openings would be formed in order to improve visual and lighting comfort. Between the two floors, a warm connection could be established by the lateral extension of the space for vertical communications using modern transparent materials.

This newly formed space would be connected to the conservatory space, which should also be provided with heat, at least during the winter season. On the facades and in the interior, it would be allowed to combine traditional - classic and modern building materials. By improving the relationship between the yard - čardak - technical facilities, the possibility of establishing a circular connection between zones opens up, as well as much greater flexibility and adaptability of the interior space of the house.

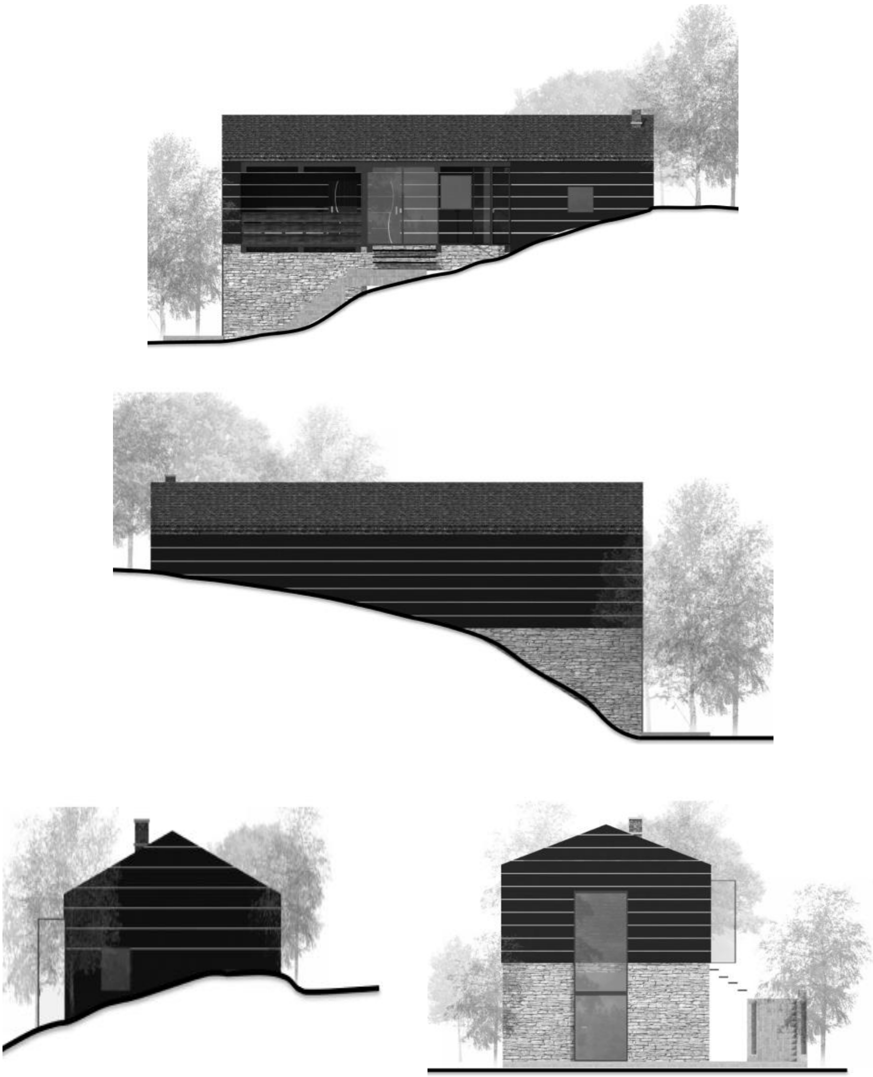


Fig. 7 Proposal for the regeneration of the house of the Stanišić family

4.2. Proposal for the regeneration of the house of the Nikolčević family

Bearing in mind that the house of the Nikolčević family (Fig. 3) is located near the old center of Štrpce**, radical interventions** on this building would refer primarily to the change of purpose from residential to hospitality. Apart from the **minimal interventions** involved, this would also mean (at least partially) the removal of internal dividing walls in order to open up the space and create toilets for guests and employees of the restaurant. The elements of the veranda remain unchanged. The lower floor could be used as a separate thematic part of the restaurant, an aperitif bar, a coffee bar or an auxiliary space that would be connected to the kitchen area on the upper floor by internal communication. In order to create a terrace for guests to stay in the open air, the terrain could also be subjected to more significant works and thus obtain sufficiently large flat surfaces.

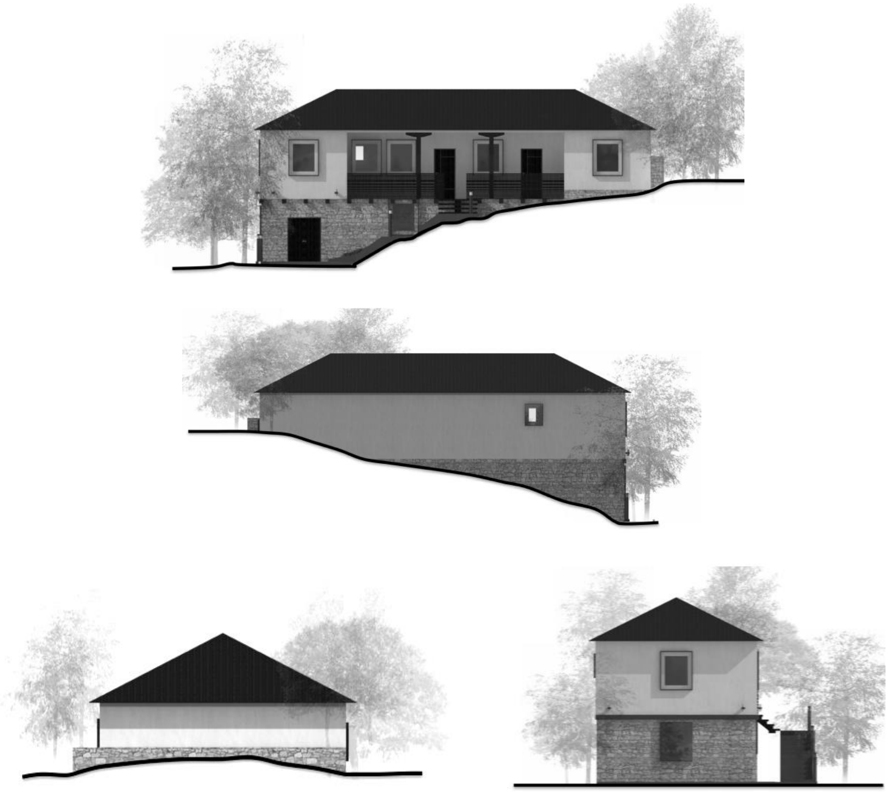


Fig. 8 Proposal for the regeneration of the house of the Nikolčević family

4.3. Proposal for the regeneration of the house of the Nikolić family

The proposal for a **medium-sized** renovation of the house of the Nikolić family in Gornja Bitinja (Fig. 4) envisages the preservation of the original purpose of the building, with the implementation of the mentioned minimally necessary interventions. Additionally, this solution would include the removal of the partition wall between the two rooms on the ground floor in order to improve the possibility of organizing a living area with a kitchen and a newly introduced bathroom. The floor would be organized as a night zone. In addition to the existing room, on this floor, by partitioning the semi-open space that was once used for the storage of fodder, an additional bedroom with an accompanying bathroom would be obtained. By closing the side wall of the house (preferably with transparent systems), the external staircase connecting the two floors would be transformed into an internal one, which would improve the comfort, functionality and connection of different parts of the house.

In another **moderately demanding variant,** the house of the Nikolić family would be turned into an ethno house. In this case, the reconstruction would entail the demolition of the partition wall between the rooms in order to obtain a larger space that can be used as a hospitality area for visitors and there would be no other significant changes.

Special attention during the regeneration should be paid to the external decoration of the otherwise spacious plot. A sufficiently large area of free space opens up additional possibilities, such as adding extensions or forming modernly interpreted "duplicates" of the house on the same plot. Building on these potentials of the location, the **radical** regeneration of the house of the Nikolić family could include the conversion of the space for permanent residence into a space for tourist accommodation.

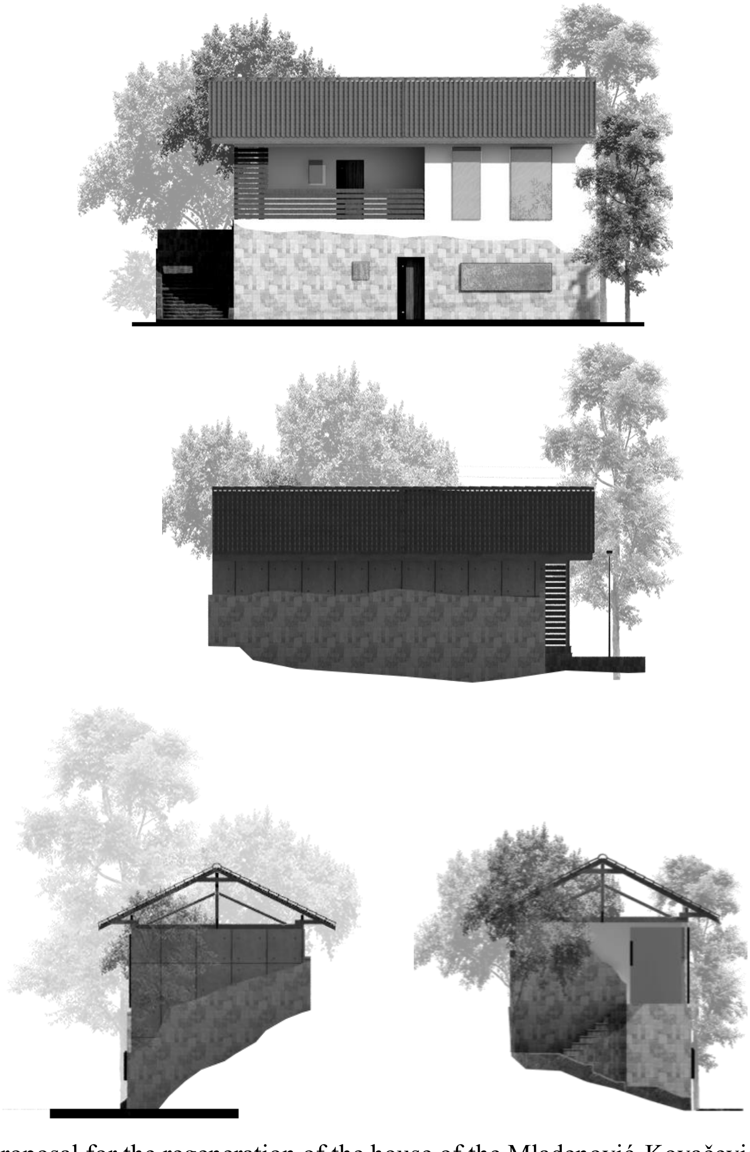


Fig. 9 Proposal for the regeneration of the house of the Mladenović-Kovačević family

4.4. Proposal for the regeneration of the house of the Mladenović-Kovačević family

As a part of **the medium-demanding** regeneration of the house of the Mladenović - Kovačević family (Fig. 5), the following interventions would be found, apart from the minimally required ones: the introduction of a bathroom in the space of the house, preferably on both floors; the introduction of modern materials that would be skillfully harmonized with the originally applied classical materials, primarily in the positions of the roof, windows and doors on the envelope; and conservatory čardak.

Since it is located near the Ski Center - Brezovica, the house of the Mladenović - Kovačević family would be transformed into a tourist and hospitality facility through **radical regeneration**. Accordingly, on the ground floor of the reconstructed entrance zone, there would be a wooden trellis and a new built-in space for storing ski equipment, and two existing rooms would be converted into a kitchen after the interventions, i.e. a shared living room with accompanying toilets. Four bedrooms upstairs would be equipped with individual bathrooms. The veranda would be extended to the level of the newly introduced canopy and then glazed.

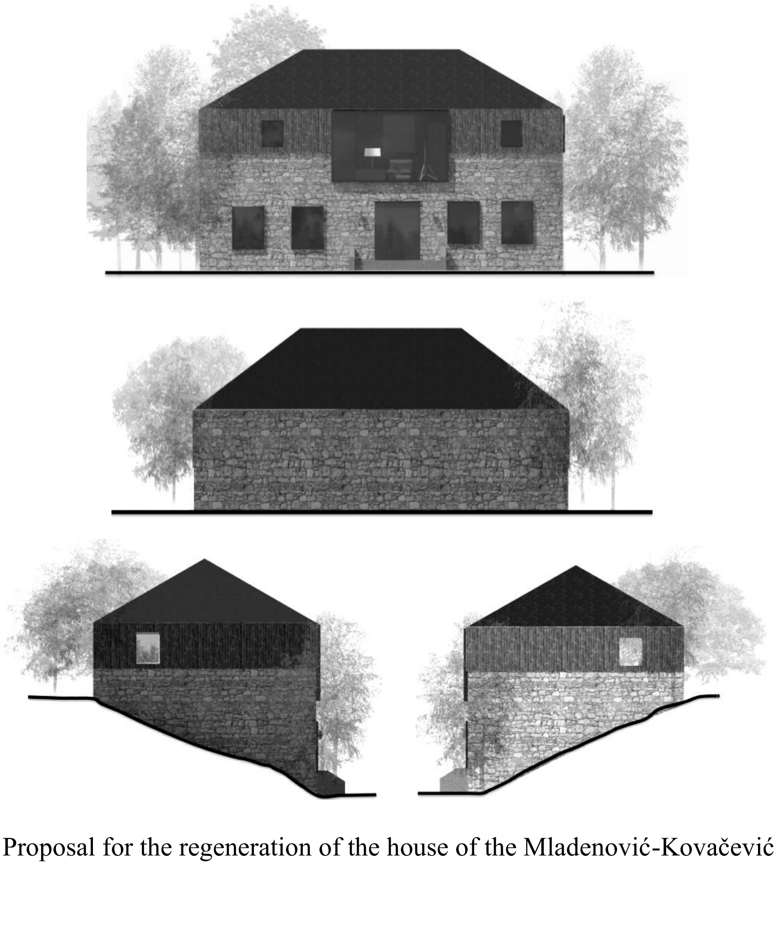


Fig. 10 Proposal for the regeneration of the house of the Mladenović-Kovačević family

4.5. Proposal for the regeneration of the house of the Kecić family

A **medium-demanding** solution for the regeneration of the house of the Kecić family (Fig. 6) would mean turning it into a catering facility that would extend through both floors. The new sanitary facilities would be adapted to the changed function and adapted to a larger number of users. Internal partitions on both floors would be maximally reduced, and the basic structure (especially the mezzanine) would be additionally secured. The exterior arrangement would be adapted to the new function, with the formation of a terrace for a larger number of people to stay in front of the house. A set of minimally necessary interventions is added to the medium-demanding solution proposal.

The proposal for **a radical intervention** involves turning the house into a tourist facility - a dispersed hotel. In addition to the minimal proposed interventions, this would also mean increasing the dimensions of the window openings, removing the barn on the first floor in order to obtain additional space for accommodation units, introducing a sufficient number of sanitary units, improving the sound protection of the partition elements and joining the original sloping ramp to the thermal envelope by glazing. The use of modern materials would also be possible in the interior. It is also proposed to frame these variants and replace the windows and doors with modern systems. In the hotel rooms, which should reflect the skillful combination of antiquity and modern functionality, only necessary pieces of furniture made of natural materials, in the spirit of an old house, with handmade details in bright colors.

When it comes to the house of the Kecić family in Štrpce, the range of minimal interventions could additionally include the removal of the partition wall between the two rooms on the ground floor - the kuća and the klećа - in order to obtain a better quality space in which the living room would be located with a kitchen and a bathroom, as well as replacing the sloping ramp with a staircase that would join the thermal envelope with glazing.

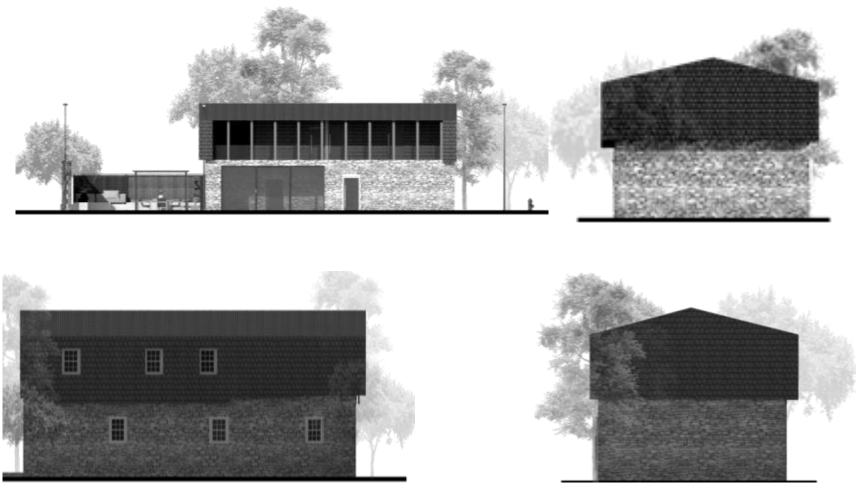


Fig. 11 Proposal for the regeneration of the house of the Kecić family

5. Conclusion

Vernacular/traditional architecture is the collective result of human behavior of changing the environment in diachronic evolution [19]. The regeneration of traditional Sirinić houses contributes to local rural socio-cultural and economic sustainability, preservation of heritage as a universal, collective good, further improvement of the ecological quality of housing units and their adaptation to current standards. In order to start this process of multiple benefits, it is necessary to develop awareness of the importance and potential of traditional built structures in the first place. Over the centuries, in all civilizations, a certain point of balance has been reached, where the peak of cultural development was translated into improved systems adapted to local conditions. This resulted in an increased and more logical use of available materials. Traditional built structures should be considered a strength, i.e., the "main economic benefit", due to the potential of conversion into tourist facilities. [20]. After that, specific local regulations and strategies need to be developed, adopted and implemented with the participation of local stakeholders (residents, homeowners and potential new end-users), investors, professionals and researchers. In the end, it is important to ensure adequate maintenance of regenerated houses because it is a prerequisite for the continued existence of the revived architectural heritage of Sirinićka Župa. The preservation of distinctive local environment and the life within the settlements and buildings is essential for sustainability in the locale. Different levels of values that are rooted in local rural communities, such as architectural, ethnological, historical and cultural, emphasize the importance of those communities. As such, it is vital to promote the purposeful use and regeneration of the architectural heritage as an integral component of new residential and tourist capacity.

References

1. Petković Grozdanovic N., Jovanović G., Stoiljković B., Petrović V., “ Adaptabilnost stambenog prostora kao parametar održivosti socijalnog stanovanja“, Nauka + Praksa, Građevinsko-arhitektonski fakultet u Nišu, vol. 21, pp. 34 - 40, 2018.
2. H. Cao, A. M. Tamás, G. Sztranyák, E. Zhang, "Regeneration and sustainable development of vernacular architecture", Pollack Periodica, An International Journalfor Engineering andInformation Sciences, vol.17, no. 2, pp. 151-156, April 2022.
3. Bulatović, S., “Cultural heritage as an initiator of urban development: the city square in Brčko“, Facta Universitatis - Series: Architecture and Civil Engineering, University of Nis, vol. 21, no. 2, pp. 325-339, 2023.
4. S. Reyhan, H. Altan, D. AlGhareeb, N. Alkhaja, "Heritage Reconstruction Planning, Sustainability Dimensions, and the Case of the Khaz'al Diwan in Kuwait", Sustainability, vol.12, no. 21, October 2020.
5. Savić, J., Romić, N., “Complexity of geotechnical problems in the process of revitalization of residential buildings ”, Facta Universitatis - Series: Architecture and Civil Engineering, University of Nis, vol. 19, no 1, pp. 55-65,2021.
6. I. Rajković, M. Bojović, "Revitalization of Traditional Architecture Towards Sustainable Development of the Skadar Lake Area", Architecture and Urban Planning, vol. 11, no.1, pp. 32-42, September 2016.
7. H. Guillaud, "Socio-cultural sustainability in architecture vernacular architecture" Versus: heritage for tomorrow, Firenze University Press, pp.48-55, 2014. 978-88-6655-741-8. ⟨hal-01159772⟩
8. K. Günçe, M. Damla. Assessment of Adaptive Reuse Practices through User Experiences: Traditional Houses in the Walled City of Nicosia. Sustainability , vol. 11, no. 2, January 2019.
9. R. L. H. Chiu, "Socio-cultural sustainability of housing: a conceptual exploration", Housing, Theory and Society, vol. 21, no. 2, pp. 65-76, June 2004.
10. B. Plevoets, K. Van Cleempoel, "Adaptive reuse as an emerging discipline: an historic survey" In G.Cairns, Reinventing architecture and interiors: a socio-political view on building adaptation, London: Libri Publishers, pp. 13-32, July 2013.

11. M. Hidayatun, J. Prijotomo, M. Rachmawa, "Sustainability is Important Part of the Identity in the Dimension of Regionalism Architecture", Applied Mechanics and Materials, vol. 747, pp.145-148, Mart 2015.
12. P. Vlahović, "Etnološke odrednice Kosova i Metohije", Etnografski muzej u Beogradu, pp. 2018. Beograd, 2004
13. D. Kuban, "The Turkish hayat house", Istanbul: T C Ziraat Bankasi / MTR, Istanbul, 1995.
14. A. Deroko, "Narodno neimarstvo, Stara seoska kuća", knj.1., Srpska akademija nauka i umetnosti, Beograd, 1968.
15. N. Gadzic, "Architecture in Sar Mountain villages", Facta universitatis - series: Architecture and Civil Engineering , vol.15, no. 3, pp. 277-294, 2017.
16. Momčilović-Petronijević A, Cvetković I, Stajić D., "Estetska degradacija objekata narodnog graditeljstva", Nauka + Praksa, Građevinsko-arhitektonski fakultet u Nišu, vol. 26, pp. 11 - 18, 2023.
17. N. Gadzic, "Seoska arhitektura Sirinićke Župe", ПАТРИМОНИУМ.МК, vol. 14, pp. 325-334, 2016.
18. T. Zhang, H. Xu, Ch. Wang, "Self-adaptability and topological deformation of Ganlan architectural heritage: Conservation and regeneration of Lianghekou Tujia village in Western Hubei, China" Frontiers of Architectural Research, Vol. 11, no. 5, pp. 865-876, October 2022.
19. Stanojević, A., Keković, A., "Functional and aesthetic transformation of industrial into housing spaces", Facta Universitatis - Series: Architecture and Civil Engineering, University of Nis, vol. 17, no. 4, pp. 401- 416, 2019.
20. S.M.C. Porto, P. M. Leanza, G. Cascone, "Developing Interpretation Plans to Promote Traditional Rural Buildings as Built Heritage Attractions", International Journal of Tourism Research, vol. 14, no. 5, pp. 421-436, September 2012.

REGENERACIJA SEOSKOG ARHITEKTONSKOG NASLEĐA: STUDIJA SLUČAJA PET TRADICIONALNIH KUĆA U SIRINIĆKOJ ŽUPI

Arhitektonsko nasleđe Sirinićke Župe, smešteno u južnom delu Republike Srbije, podno Šarske planine, najpoznatije je po tradicionalnim kućama. Jedinstvenost stila starih sirinićkih kuća pripisuje se upotrebi lokalnih materijala i prilagođavanju lokalnoj topografiji, klimi i morfologiji naselja. Studija prepoznaje značaj čuvanja autentičnosti stambenog arhitektonskog nasleđa Sirinićke Župe i ističe potrebu za razumevanjem potencijala ovih građevina radi određivanja budućih odgovarajućih intervencija. Konkretnije, istraživanje analizira razvoj tradicionalne stambene arhitekture u području Sirinićke Župe, fokusirajući se na pet karakterističnih i reprezentativnih primeraka kuća - njihov originalni koncept i vrednost, trenutno stanje i pravac regeneracije. Rezultati doprinose postojećem korpusu literature pružanjem detaljnog naučnog opisa vrednosti sirinićkih kuća, kao i opravdanih intervencija u vezi sa regeneracijom koje proizilaze iz delikatnog pristupa i procene uticaja.

Ključne reči: *tradicionalne kuće, Sirinićka Župa, regeneracija, održivi razvoj sela*

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GROUND IMPROVEMENT AND FOUNDATION DESIGN OF INDUSTRIAL FACILITIES ON LOESS SOIL

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Abstract. *This study addresses the exploration of two interchangeable foundation strategies for an industrial site (silo base) located in Silistra, Bulgaria. The geological conditions at the site present significant challenges due to the presence of local loess soil, which has been classified as "collapsible – Type II" in accordance with the Bulgarian Shallow Foundations Code, extending to a depth of 12 meters. To adhere to the code requirements and meet the stringent operational limitations imposed on the silos, including restrictions on foundation settlement and tilt, two potential approaches are considered. These options involve either mitigating the collapsibility of the soil or navigating through the collapsible soil using deep foundation techniques like piles, slurry walls, and similar methods. Following an initial technical analysis and cost estimation, this study favors the utilization of shallow foundation methods combined with local soil improvement practices. The first approach entails the construction of a dual mat foundation, which is placed atop a relatively thick base layer comprising a soil-cement mixture and soil that has been enhanced through rapid impact compaction (RIC). The second approach involves a mat foundation positioned on a relatively thinner base layer of soil-cement mixture, supplemented by strategically placed deep soil mix (DSM) columns. Both of these strategies ensure the structural reliability of the silos, advocate for the implementation of soil improvement methods readily accessible within the Bulgarian market, and offer a swift and cost-efficient execution.*

Key words: *loess, collapsible soil, shallow foundation, soil improvement, silo, rapid impact compaction, cement-soil mixing, deep soil mixing*

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1. INTRODUCTION

Collapsible soils present significant challenges in geotechnical and structural engineering worldwide. They can occur naturally or due to human activities, involving unstable structures with various bonding mechanisms. Bonds may form through capillary forces or cementing materials, and collapse happens when applied stresses exceed the yield strength of these bonds. Collapsibility is often triggered by water inundation, which varies in impact. Effective management of collapsible soils requires accurate identification, based on geological and geomorphological data, along with wetting-loading tests. Spatial distribution and wetting extent are crucial considerations. Soil improvement techniques can mitigate collapse potential. Common features of collapsible soils include unstable open structure, high voids ratio, high porosity, recent deposits, high sensitivity, and weak interparticle bonding.

Collapsible loess soils, composed of fine quartz particles, are widespread in various regions globally, posing collapse risks. Understanding soil particle Provenance, Transportation, and Deposition sequences is vital in developing a collapsible structure. Wind direction and climate fluctuations influence collapsibility zones, water infiltration, and ground improvement effectiveness.

sequences is vital in developing a collapsible structure. Wind direction and climate fluctuations influence collapsibility zones, water infiltration, and ground improvement effectiveness.

Loess soils, covering approximately 9800 km^2 in Northern Bulgaria, vary in thickness from 1 m in the Balkan Mountains to over 100 m along the Danube River. These soils have aeolian origins, transported mainly from the north-northeast winds during the late Pliocene and early Quaternary periods. Sources include the Paleodanube floodplains, shaped by glacial denudation of the Eastern Carpathians slopes. Bulgarian loess is characterized by high silt content, ample pores, macropores, low dry density, and relatively low moisture levels. Buried soil horizons form during periods of reduced dust deposition, resulting in six distinct loess varieties. In the northern Danube Plain of Bulgaria, construction-related challenges arise due to loess subsidence upon saturation, primarily in typical loess, sandy loess, and clayey loess.

Due to the diverse geomorphological processes contributing to loess formation, loess deposits typically exhibit three distinct zones of relative collapsibility:

- Zone 1: This zone is situated at a depth where material collapses due to overburden pressure.
- Zone 2: Known as the collapsible zone, this layer is susceptible to collapse.
- Zone 3: The surface crust, requiring additional load to induce collapse.

Countries with extensive loess deposits, such as Eastern Europe and the former Soviet Union, have developed classification systems related to foundation collapse under loading. These schemes categorize collapsibility into two types:

- Type I: Mainly associated with loaded collapsibility, where collapse deformation occurs under an overburden pressure of less than 5 cm.
- Type II: Primarily linked to unloaded collapsibility, characterized by collapse induced deformation more than 5 cm.

Type I loess is typically of limited thickness and contains one or two palaeosols (PS) along with an associated carbonate zone (Cz). Collapse in Type I loess occurs once the foundation stress surpasses a critical stress threshold, determinable through laboratory or field tests.

The focus of this report is a planned industrial base in Northern Bulgaria, specifically in Silistra municipality. The investment intentions revolve around a silo farm, comprising 44 silos, each with a volume of 12 500 m^3, organized into 11 groups of 4 each, resulting in a total volume of up to 50 000 m^3. Additionally, there are 11 truck unloading stations, two truck scales with a capacity of 60 t and a length of 18 m, a checkpoint, and related facilities.

The development involves the foundation of the aforementioned silos, each consisting of a cylindrical body and a conical roof, both constructed from galvanized trapezoidal sheet metal. These facilities are designed for the storage of various types of grain, with a focus on wheat storage in this case. The dimensions of the silos are as follows: a diameter of 25.47 m, a height of the cylinder to the roof of 22.92 m, and a height of the conical roof of approximately 7.2 m.

The maximum load capacity is approximately 15 t, and comprehensive calculations have been conducted, considering two primary load scenarios from a technological perspective: SYM (symmetric silo emptying) and SD (one-sided silo emptying). The accepted absolute elevation for the site is ±0.00, with a reference point at 120.00 m.

The permissible settlement limit, according to [1] and [2] (National Annex – NA), is 15 cm, and that of permissible rotation is 4‰. Additional technological requirements for the facilities provide stricter values, specifically 5 cm for settlement and 2‰ for rotation. To ensure the optimal operation of the facilities and achieve the best technical and economic solution, the following final limit values have been adopted:

- Densification settlement should not exceed 5 cm.
- The combined settlement from densification and collapse shall not exceed 15 cm.
- Rotation due to subsidence from compaction should not exceed 2‰.
- Rotation resulting from densification settlement and collapse induced settlement should not exceed 4‰.

The current development examines the foundation structure of the silo base and the measures for improving soil’s physical and mechanical, taking into account the specific geological conditions and the loads imposed by the structures. Two alternative and interchangeable foundation options, from a technical perspective, are proposed.

2. GEOLOGICAL CONDITIONS

Geological surveys of the construction site, located at an altitude of 117.00 to 122.0 m, were conducted by a team of engineering geologists in April 2022. Fifteen boreholes (from BH1 to BH15) were drilled (plan view of the borehole locations and a geological section are on Fig. 1 and Fig. 2, respectively). Due to the uneven terrain, BH1 to BH9 and BH13 to BH14 are situated in the higher part, while boreholes BH10 to BH12 and BH15 are in the lower part. These boreholes reached a total depth of 191 m, and 191 soil samples, both disturbed and undisturbed, were collected and examined.

The site's ground base primarily consists of loess deposits, which extend to a depth of over 20 m. These deposits consist of alternating loess horizons and buried soils. The thickness of the first and second loess horizons, separated by a buried soil layer, ranges from 12.00 to 12.50 m.

Below the second loess horizon, additional layers include a second buried soil, a third loess horizon, and basic loess clays. Notably, the loess horizons are thicker than the buried soils. The geological section concludes with a young soil layer, which has a limited thickness compared to flat terrain due to erosion processes, particularly pronounced in sloping areas. It is important to note that shallow groundwater is absent in the area.

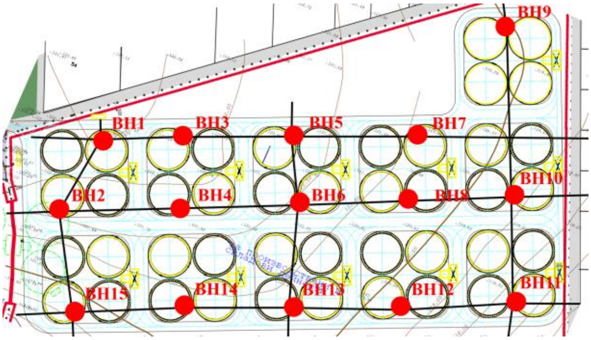

Fig. 1 Plan view of the locations of the boreholes

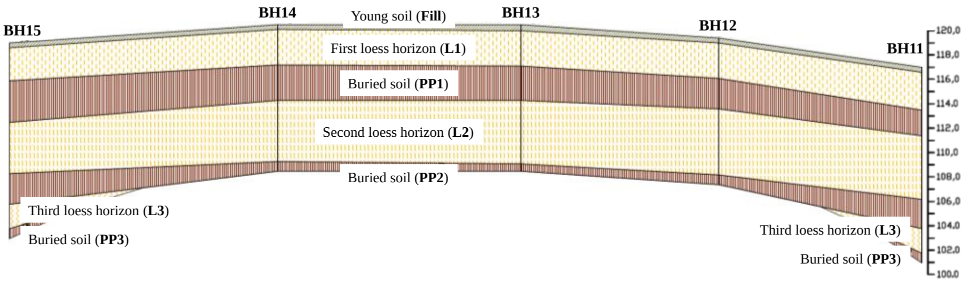

Fig. 2 Geological section through BH11, BH12, BH13, BH14 and BH15

The loess deposits comprising the site's ground base are prone to collapsing. Research has revealed that the first and second loess horizons, the intervening buried soil, and the upper half of the second buried soil layer all experience collapse when wet and subjected to geological and additional loads. The thickness of the collapse layer can reach up to 12 m, and the relative collapse coefficient (δ_p) at a stress of 300 kPa varies, falling within the range of 0.016 to 0.080.

Table 1 Elevation and depth of the boreholes

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14				BH10, BH11, BH12 & BH15			
					Top level Bot. level [m]	Top Bottom [m]	Height [m]	Total height [m]	Top level Bot. level [m]	Top Bottom [m]	Height [m]	Total height [m]
120.00	-	FILL	NONE	NO	-	-	-	-	120.00	0.00	1.70	16.80
	1	YOUNG SOIL			-	-	-	-	118.30	-1.70		
	2	LOESS - L1		YES	120.00 117.60	0.00 -2.40	2.40	13.70	118.30 115.30	-1.70 -4.70	3.00	
	3	BURIED SOIL - PP1		YES	117.60 114.80	-2.40 -5.20	2.80		115.30 112.70	-4.70 -7.30	2.60	
	4	LOESS - L2		YES	114.80 109.60	-5.20 -10.40	5.20		112.70 107.60	-7.30 -12.40	5.10	
	5	BURIED SOIL - PP2		YES	109.60 108.80	-10.40 -11.20	0.80		107.60 106.00	-12.40 -14.00	1.60	
	6	LOESS - L3		NO	108.80 107.10	-11.20 -12.90	1.70		106.00 104.00	-14.00 -16.00	2.00	
	7	BURIED SOIL - PP3		NO	107.10 106.30	-12.90 -13.70	0.80		104.00 103.20	-16.00 -16.80	0.80	

Table 2 Physical parameters of the soils

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	Physical Parameters									
					γ_n	γ_s	γ_d	γ'	γ_r	e	n	w_n	w_r	S_r
					[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[-]	[-]	[%]	[%]	[-]
120.00	-	FILL	NONE	NO	18.50	26.00	16.00	10.00	20.00	0.60	0.38	-	23.08	-
	1	YOUNG SOIL												
	2	LOESS - L1		YES	16.19	26.49	13.73	8.33	18.33	0.980	0.495	16.10	37.00	0.44
	3	BURIED SOIL - PP1		YES	16.78	26.49	13.83	8.37	18.37	0.969	0.492	21.30	36.57	0.58
	4	LOESS - L2		YES	17.27	26.49	14.81	8.54	18.54	0.931	0.482	18.40	35.15	0.52
	5	BURIED SOIL - PP2		YES	18.54	26.49	15.21	8.74	18.74	0.887	0.470	22.00	33.48	0.66
	6	LOESS - L3		NO	18.15	26.49	15.01	8.24	18.24	1.000	0.500	21.00	37.75	0.56
	7	BURIED SOIL - PP3		NO	19.42	26.49	15.70	8.24	18.24	1.000	0.500	23.80	37.75	0.63

Table 3 Deformation parameters of the soils

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	Deformation Parameters							
					ν	$\delta_{pr,300kPa}$	p_0	E	E_d	$E_{oed,0.1MPa}$	$E_{oed,0.2MPa}$	$E_{oed,0.3MPa}$
					[-]	[%]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]
120.00	-	FILL	NONE	NO	0.300	-	-	10000	30000	10000	15000	20000
	1	YOUNG SOIL										
	2	LOESS - L1		YES	0.325	4.8	62	10250	9500	4100	4400	3500
	3	BURIED SOIL - PP1		YES	0.325	2.3	128	11000	10000	4400	5600	7800
	4	LOESS - L2		YES	0.325	4.5	66	15250	12000	6100	8000	9500
	5	BURIED SOIL - PP2		YES	0.325	1.0	300	14000	18000	5600	7700	10800
	6	LOESS - L3		NO	0.325	-	-	14000	18000	5600	7700	10800
	7	BURIED SOIL - PP3		NO	0.325	-	-	23335	30000	9334	12834	18000

Table 4 Strength parameters of the soils

Level +/- 0.00	Layer No.	Soil Type	G.W.T.	Collapse	Strength Parameters			
					φ	c	c_u	R_0
					[°]	[kPa]	[kPa]	[kPa]
120.00	-	FILL	NONE	NO	35.00	0.00	0.00	250
	1	YOUNG SOIL						
	2	LOESS - L1		YES	23.00	5.00	50.0	160
	3	BURIED SOIL - PP1		YES	21.00	7.00	70.0	160
	4	LOESS - L2		YES	25.00	7.00	70.0	170
	5	BURIED SOIL - PP2		YES	20.00	15.00	150.0	200
	6	LOESS - L3		NO	22.00	20.00	200.0	200
	7	BURIED SOIL - PP3		NO	19.00	35.0	350.0	250

Overall, research in the area classifies the ground base as a pronounced Type II, following [3] criteria. This means that it is expected to undergo collapse upon wetting, but only when subjected to geological loads of approximately 15 to 25 cm, surpassing the 5 cm threshold. Visible humidity anisotropy is observed up to a depth of 9 to 10 meters, with the underground water level extending to a depth of 16.00 meters. Unfavorable geological phenomena and processes were not identified, except for the collapsibility of the loess and high seismic activity.

The results of the geological survey and additional data, as assessed by the author, are organized as depicted in Tables 1, 2, 3, and 4. To determine the initial collapse stress (p_0), the relative collapse coefficient (δ_p) at 300 kPa for each failure layer in the "stress-relative collapse coefficient" relationship was used. The initial collapse stress (p_0) is graphically defined for δ_p=1% (see Figure 3). The most significant geological feature is that layers of the first loess horizon (L1), the first buried soil (PP1), the second loess horizon (L2), and the second buried soil (PP2) exhibit collapsibility (with a volume of macropores, n_m, exceeding 1%). They are classified as Type II according to [8], indicating that the collapse due to the soil's own weight exceeds 5 cm. The depth of subsidence reaches approximately 11.20 meters below the established site elevation of ±0.00, which is referenced to a relative elevation of 120.00 meters, or roughly 109.30 meters.

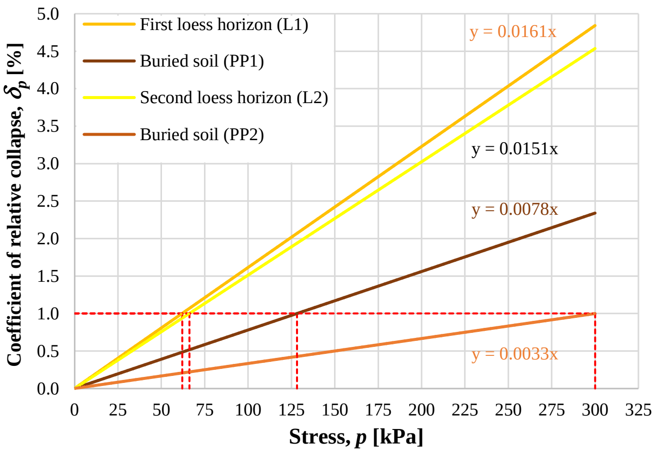

Fig. 3 Procedure for evaluation coefficient of relative collapse

Designing foundation structures on Type II soil foundations, as per [3], requires determining the following:

1. The maximum collapse induced settlement ($s_{collapse}$) occurring when the entire subsidence zone becomes fully saturated with water ($h_{collapse}$) due to extensive flooding or a rise in the water level.
2. The potential failure that occurs in the event of localized wetting of an area narrower than the failure zone's width.

Total settlement is calculated as the sum of vertical deformation from soil densification and subsidence from loess collapse when wetted. Design considerations must account for the possibilities of soil moisture increase due to:

1. Localized (partial) inundation of the soil foundation by emergency water, leading to collapse in a limited area.
2. Extensive inundation of the soil foundation across a substantial area, covering the entire failure zone height.
3. Rising groundwater levels.
4. Gradual increase in water content in problematic layers caused due to alterations in natural hydrogeological conditions.

3. Settlement Evaluation Procedure

An analysis of settlements was conducted using three independent methods, incorporating classical computational approaches such as the method of layer-by-layer summation and stress distribution based on the Westergaard method (see Fig. 4), along with the finite element method (FEM – Mohr-Coloumb constitutive model) in geotechnics, known for its high precision (see Fig. 5 and Fig. 6).

In the context of shallow foundations in geotechnical engineering, the Mohr-Coulomb constitutive model is particularly valuable. It helps assess the stability and load-bearing capacity of these foundations by considering soil properties like cohesion and internal friction angle.

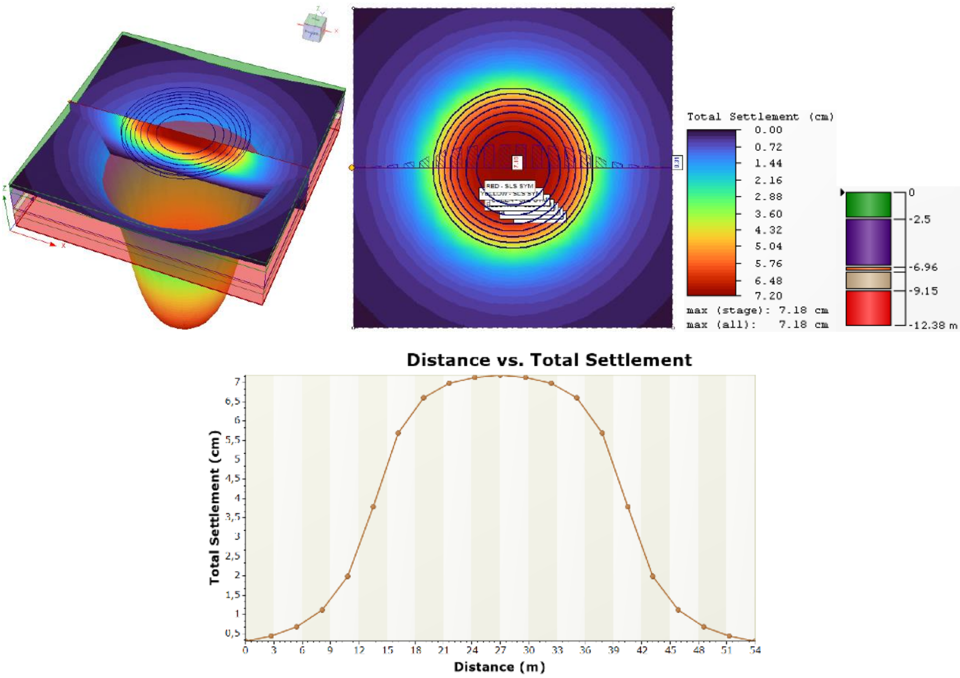

Fig. 4 Westergaard stress distribution (analytical solution) results: foundation base at +116.35 – mean settlement for SLS-SYM combination

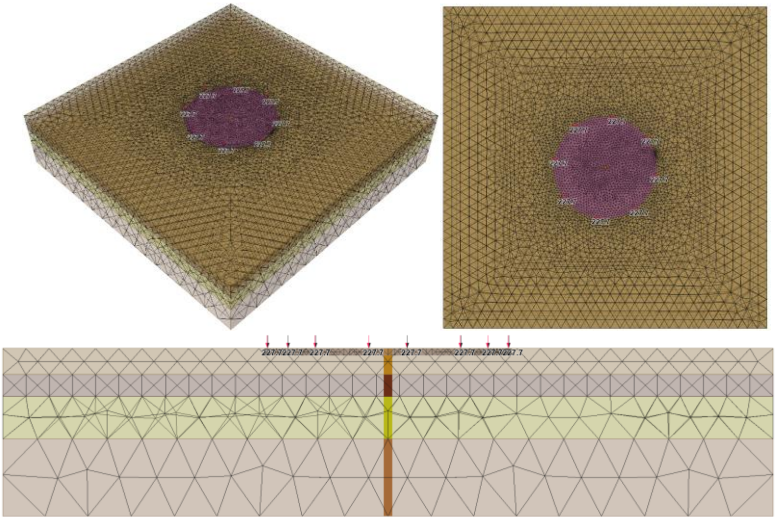

Fig. 5 Overview of the FEM model

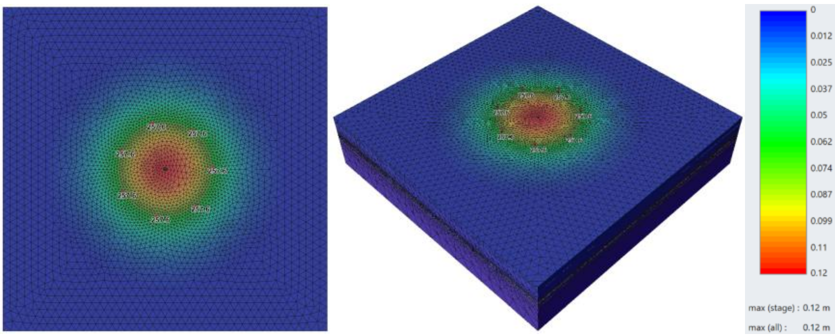

Fig. 6 FEM (Mohr-Coloumb constitutive model) results: foundation base at +116.35 – mean settlement for SLS-SYM combination

Shallow foundations, which include footings and mats, rely on the soil directly beneath them to support the structure's loads. The Mohr-Coulomb model allows engineers to analyze how different soil types and conditions will behave under the applied loads, helping ensure the safety and longevity of structures resting on shallow foundations. By understanding the soil's shear strength characteristics through this model, engineers can make informed decisions about foundation design, soil improvement, and construction techniques to prevent settlement, tilting, or failure. In the design of shallow foundations, several key aspects must be considered, including bearing capacity (both structural and geotechnical) and settlement, as outlined in [1] and [2]. In the presented practical case, the aspect related to settlement is particularly critical. The active subsidence zone has been determined to be at a depth of 12.50 meters, in accordance with the recommendations of [3] for wide-area (mat) foundations.

4. Soil Improvement and Foundation Concept

The study presents two interchangeable foundation construction concepts as follows:

1. A double reinforced concrete slab with connecting vertical structural elements (columns) with a height of 4.15 meters - the foundation base is at elevation +116.35.
2. A single reinforced concrete slab (F-type) with a height of 2.10 meters – the mat base falls at elevation +116.35.

Both solutions provide functionality, with technological installations (pipes) placed between the two slabs in one version and within channels formed in the structure in the other. They also ensure reliable broad-area load transmission from the superstructure to the ground base, preventing stress concentration and ensuring even settlements.

In the first iteration, options were considered without improving the soil parameters by placing the foundation structures directly on the virgin ground – Table 5. The stress distribution in depth for the two foundation cases is shown in Fig. 7.

Table 5 Evaluated settlement for a case without soil improvement

Foundation concept	**Location according to the geological survey**	**Without soil simprovement**						
		Densification				Collapse	**Total**	
		Layer-by-layer Sum	Westergaard Method	FEM		Layer-by-layer Sum	Layer-by-layer Sum	Layer-by-layer Sum
				Mohr-Coloumb	HSM			
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
Double mat foundation at +116.35	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	13.98	14.40	19.00	**0.18**	31.89	**45.87**	**46.29**
	BH10, BH11, BH12 & BH15	16.52	16.70	21.00	**0.18**	35.90	**52.42**	**52.60**
Single mat foundation at +118.40	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	14.46	14.20	19.00	**0.16**	34.13	**48.59**	**48.33**
	BH10, BH11, BH12 & BH15	16.20	15.60	22.00	**0.16**	44.85	**61.05**	**60.45**

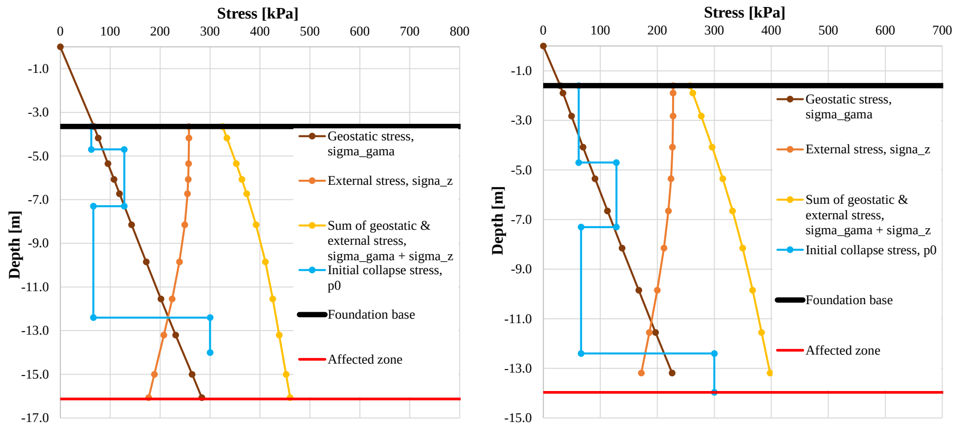

Fig. 7 In-depth stress distribution for the two types of foundations at different elevation of the base – without soil improvement

The results clearly demonstrate that the settlements exceed the accepted limit values, with subsidence being the dominant contributor, reaching values of approximately 50 to 60 cm. Therefore, treating the entire failure zone up to an elevation of 109.30 m (-11.20) is essential for the conceptual foundation decisions. An exception is the finite element method solution (Hardening Soil constitutive model), which, although it usually yields realistic results, should not be definitively adopted due to the lack of reliably determined parameter values in geological survey. It is provided for informational purposes, while the other three independent methods described above were used for calculations.

In accordance with [3], three types of measures to reduce the effect of soil subsidence are given:

1. Removal of soil collapsible properties through compaction or strengthening: surface compaction, laying compacted soil or cement-soil cushions, silicification, cementation, heat treatment, etc.
2. Protection of the ground base from flooding: proper placement of the structures, constructing watertight screens under buildings, laying pipelines in troughs and casings, implementing leak detection systems, etc.
3. Structural measures (Fig. 8): using structural systems that are insensitive to uneven settlements, increasing the stiffness of the underground part of the buildings (facilities), increasing foundation depth, passing the failure layer with a deep foundation, etc.

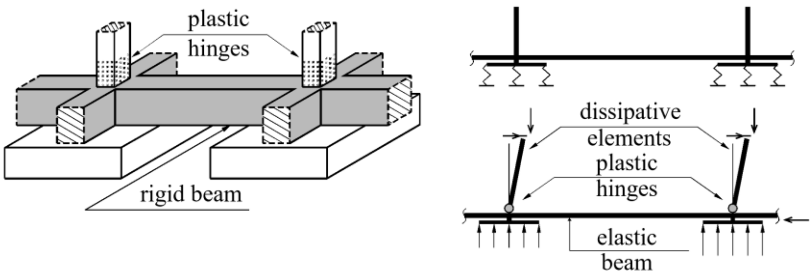

Fig. 8 Continuous footing design for collapsible soils

Additionally, with a Type II soil (loess) type, a screen should be created under the entire building or facility – [4]. Considering the above, two final foundation options have been proposed – Fig. 9 and Fig. 10.

1. Option 1: A foundation structure with a double bottom (4.15 m high), a 2.5 m cement-soil cushion, and rapid impact compacted soil, as described in references [5] and [6], with dimensions of approximately 4.55 m. In total: 4.15 m (foundation height) + 2.5 m (cement-soil cushion – CSC) + 4.55 m (compacted soil) = 11.20 m, which should effectively address the issue of the collapsible zone. Rapid Impact Compaction (RIC) is a dynamic soil improvement technique appreciated for its efficiency and cost-effectiveness. RIC is a method that involves the utilization of heavy machinery equipped with a specialized compaction hammer. This powerful equipment delivers a sequence of impactful blows to the ground surface, inducing soil densification and bolstering its load-bearing capacity. Renowned for its swift and budget-friendly approach, RIC has emerged as a favored choice in the realm of construction and infrastructure development. Its

primary role is to swiftly fortify weak or loose soils, mitigating the likelihood of settlement-related challenges and ensuring a stable foundation for various structures. Option 1 includes increasing the embedment depth, a robust reinforced concrete box beneath elevation ±0.00 and the elimination of soil collapsibility. Additionally, measures for waterproofing will be implemented, as mandated for Type II soil conditions according to [3]. Before commencing ground improvement activities, an experimental section should be provided to demonstrate the applicability of rapid impact compaction. Compaction using rammers is applied to soils with a degree of water saturation (S_r) less than 0.7 and a density not exceeding 1.6 g/cm^3. While the degree of water saturation condition is met in this specific case, the bulk density requirement of less than 1.6 g/cm^3 is not satisfied. Nevertheless, based on prior experience, the author remains confident in the positive results achievable through this compaction technique. Historical evidence from similar previous projects using this method suggests that "impulse compaction" effectively enhances soil layers with thicknesses ranging from 3.5 to 8 m. Settlement data is organized in Table 6 for reference.

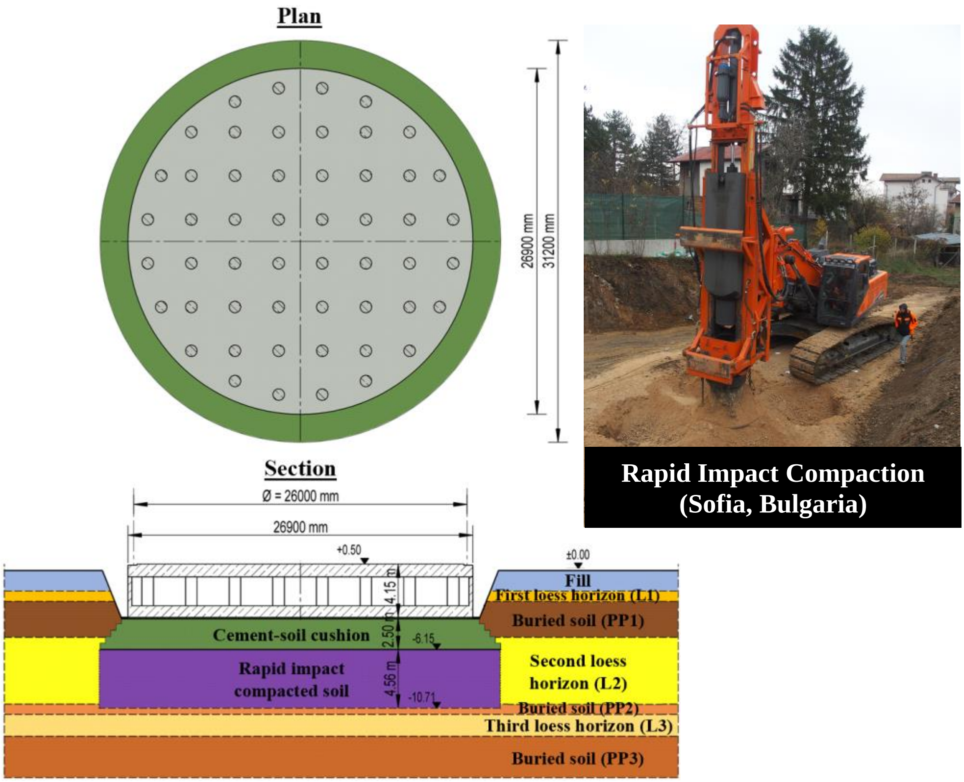

Fig. 9 *Option 1*: double foundation mat, thick cement-soil cushion and rapid impact compaction

2. Option 2: The foundation structure, F-type, consists of a single bottom (2.10 m high), a 0.6 m cement-soil cushion (CSC), and deep soil mixing columns – [7] and [8]. There are a total of 103 columns with a diameter of *D*=1.20 m and a length of 8.50 m for all the silos, accounting for 17.5% of the collapsible zone. The overall treatment depth is calculated as follows: 2.10 m + 0.6 m + 8.50 m = 11.20 m, which is sufficient to overcome the collapsible zone. Deep Soil Mixing (DSM) is a construction technique that strengthens weak or unstable soils by mechanically blending them with cementitious materials. Specialized equipment injects the binder as it penetrates the ground, creating soil-cement columns with improved strength and durability. DSM is versatile, suitable for various soil types, and environmentally friendly as it reduces the need for soil disposal. It is a preferred choice for geotechnical challenges in construction. Option 2 assumes the removal of any unfavorable soil properties. The cement-soil cushion (CSC) serves not only as a waterproof screen but also activates the deep soil mixing columns evenly within the zone. Furthermore, water protection measures will be implemented, in accordance with the requirements for a Type II soil conditions as specified in [3]. Prior to applying the technology for the execution of the deep soil mixing columns, an experimental section will be designated. The settlements are presented in Table. 7.

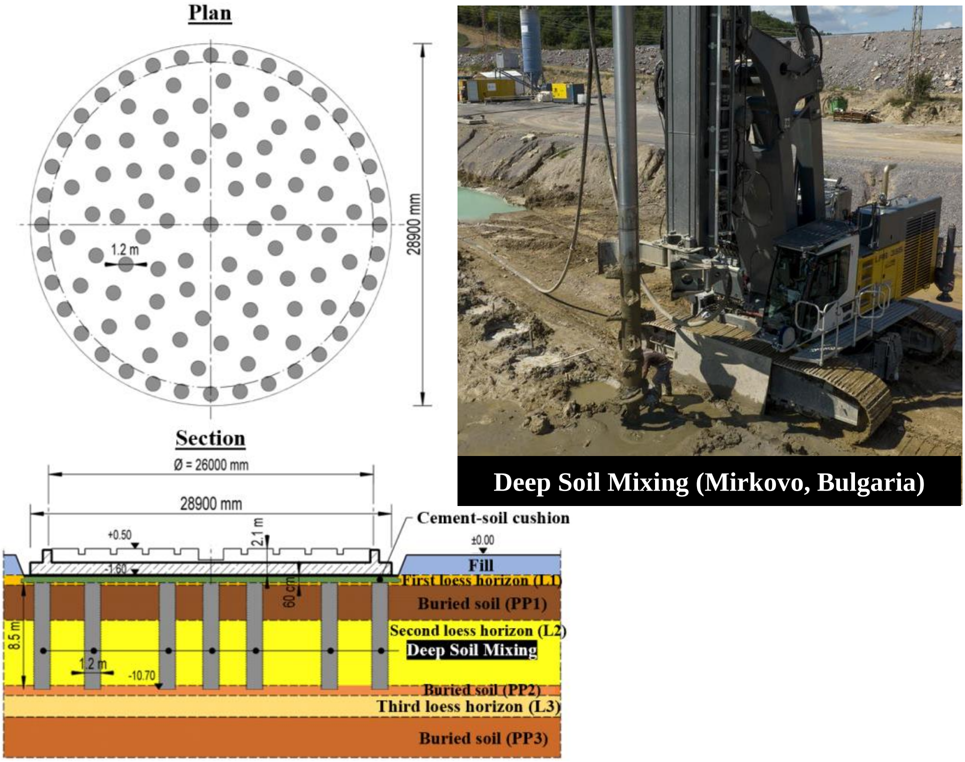

Fig. 10 *Option 2*: single mat foundation, thin cement-soil cushion and deep soil mixing columns

Both types of loading conditions, SYM (symmetric silo discharge) and SD (single-sided silo discharge), lead to further subdivisions of foundation types. All the ground improvement measures described above remain valid. SD condition leads to tensile stresses in the main plane of the foundations, which can be resolved in two ways:

- For *Option 1*: Tension is eliminated by joining adjacent silos in a common foundation mat, while all other ground improvement measures remain in effect.
- For *Option 2*: Tension is eliminated by uniting adjacent silos in a common foundation mat or embedding steel profiles in the outer two rings of DSM columns (the profiles are anchored to the foundation mat). Once again, all other ground improvement measures remain in effect.

Based on the author's previous experience and that of the geotechnical community in Bulgaria, the estimated amount of cement for forming the cement-soil cushions is 6% to 8% of the solid phase of the soil – [9] and [10]. It is advisable to use sulfate-resistant cement. The amount of water to be added should be determined based on the optimum water content obtained from Proctor tests.

Table 6 Evaluated settlement for *Option 1*: double foundation mat, thick cement-soil cushion and rapid impact compaction

Foundation concept	Location according to the geological survey	Thick cement-soil cushion (CSC) & rapid impact compaction						
		Densification				Collapse	Total	
		Layer-by-layer Sum	Westergaard Method	FEM		Layer-by-layer Sum	Layer-by-layer Sum	Layer-by-layer Sum
				Mohr-Coloumb	HSM			
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
Double mat foundation at +116.35	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	6.01	7.18	12.00	-	0.49	**6.50**	**7.67**
	BH10, BH11, BH12 & BH15	7.69	8.24	13.00	-	9.31	**17.00**	**17.55**
Single mat foundation at +118.40	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	-	-	-	-	-	-	-
	BH10, BH11, BH12 & BH15	-	-	-	-	-	-	-

Table 7 Evaluated settlement for *Option 2*: single mat foundation, thin cement-soil cushion and deep soil mixing columns

Foundation concept	Location according to the geological survey	Thin cement-soil cushion & deep soil mixing (DSM)						
		Densification				Collapse	Total	
		Layer-by-layer Sum	Westergaard Method	FEM		Layer-by-layer Sum	Layer-by-layer Sum	Layer-by-layer Sum
				Mohr-Coloumb	HSM			
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
Double mat foundation at +116.35	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	-	-	-	-	-	-	-
	BH10, BH11, BH12 & BH15	-	-	-	-	-	-	-
Single mat foundation at +118.40	BH1, BH2, BH3, BH4, BH5, BH6, BH7, BH8, BH9, BH13 & BH14	2.71	3.31	7.40	-	0.50	**3.21**	**3.81**
	BH10, BH11, BH12 & BH15	3.61	3.54	8.80	-	9.28	**12.89**	**12.82**

5. Comparison of Foundation Concepts

The advantages and disadvantages of the two proposed foundation options have been meticulously evaluated, drawing upon the author's previous experience and a comprehensive technical-economic analysis is demonstrated on Table 8. Preliminary evaluation suggests Option 1 as more suitable technique for the particular project.

Table 8 Benefits and drawbacks of the two suggested soil improvement methods

Criteria / Foundation concept	**Option 1: Thick cement-soil cushion (CSC) & rapid impact compaction (RIC)**	**Option 2: Thin cement-soil cushion (CSC) & deep soil mixing (DSM)**	**Comment**
Bearing capacity check	O	O	-
Mean settlement check	O	O	After proving the applicability of rapid impact compaction.
Applicability	△	O	Applicability of rapid impact compaction shall be proved.
Foolproofness	O	X	-
Price	△	△	Cheaper solution has to be chosen on the basis of offers.
Duration	X	O	-

6. Conclusion

The presented paper delves into the exploration of two interchangeable foundation strategies for an industrial site in Silistra, Bulgaria, confronted with challenging geological conditions, mainly due to 'collapsible – Type II' loess soil. The study considers options to mitigate soil collapsibility and enable efficient foundation construction for silos. After a thorough technical analysis and cost assessment, the study favors shallow foundation methods combined with local soil improvement practices. Two approaches are presented: a double mat foundation on a thick soil-cement cushion (CSC) and a single mat foundation on a thinner soil-cement cushion (CSC) with DSM columns below. Both ensure structural integrity, utilize readily available soil improvement techniques, and offer cost-effective execution. The research highlights the dominance of collapse subsidence over densification settlement, with advanced computational methods confirming realistic densification vertical displacements. However, adhering to safety and responsibility, addressing soil failure properties up to an elevation of 109.30 m is crucial to mitigate potential catastrophic consequences.

References

1. European Committee for Standardization, “Eurocode 7: Geotechnical Design - Part 1: General Rules”, CEN (European Committee for Standardization), 2012.
2. European Committee for Standardization, “Eurocode 7: Geotechnical Design - Part 2: Ground Investigation and Testing”, CEN (European Committee for Standardization), 2012.
3. Ministry of Territorial Development and Construction, „Standards for Shallow Foundation Design (in Bulgarian)“, State Gazette, 1996.
4. M. Minkov and D. Evstatiev, “Foundations, covers and screens of improved loess soils (in Bulgarian)”, Tehnika Sofia, 1975.
5. D. Adam and I. Paulmich, “Rapid impact compactor–an innovative compaction device for soil improvement”, In Proceedings of the 8th International Geotechnical Conference, 2007, pp. 183–193.

6. C. J. Serridge and O. Synac, “Application of the rapid impact compaction (RIC) technique for risk mitigation in problematic soils”, In 10th IAEG International Congress, paper no. 294, 2006.
7. M. Kitazume, “Quality Control and Assurance of the Deep Mixing Method”, CRC Press (Taylor and Francis Group), 2022.
8. M. Kitazume and M. Terashi, “The Deep Mixing Method”, CRC Press (Taylor and Francis Group), 2013.
9. R. Angelova and D. Evstatiev, “Strength gain stages of soilcement”, In Proceedings of 6th Interantional IAEG Congress, 1990, pp. 3147–3154.
10. D. Evstatiev, D. Karastanev, R. Angelova and I. Jefferson, “Improvement of collapsible loess soils from Eastern Europe: Lessons from Bulgaria”, In Proceedings of the 4th International Conference on Ground Improvement Techniques, 2002, pp. 331–338.

UNAPREĐENJE TLA I PROJEKTOVANJE TEMELJA INDUSTRIJSKIH OBJEKATA U LESNOM ZEMLJIŠTU

Ovaj istraživački rad bavi se ispitivanjem dve međusobno zamenljive strategije za fundiranje industrijske lokacije (osnove silosa) koja se nalazi u Silistri, Bugarska. Geološki uslovi na ovoj lokaciji predstavljaju značajne izazove zbog prisustva lokalnog lesnog zemljišta, koje je klasifikovano kao 'sklopivo - tip II' u skladu sa bugarskim kodeksom o plitkim temeljima i prostire se do dubine od 12 metara. Da bi se odgovorilo na zahteve kodeksa i ispunila stroga operativna ograničenja koja važe za silose, uključujući ograničenja na sleganje i nagib temelja, razmatraju se dva potencijalna pristupa. Ove opcije uključuju ili ublažavanje sklopivosti tla ili navigaciju kroz sklopivo tlo koristeći tehnike dubokih fundamenata kao što su šipovi, zidovi od gline i slični metodi. Nakon početne tehničke analize i procene troškova, ova istraživanja se zalažu za korišćenje metoda plitkih fundamenata u kombinaciji sa lokalnim praksama unapređenja zemljišta. Prvi pristup uključuje izgradnju dvostrukih mat fundamenata, koji se nalaze na relativno debelom osnovnom sloju koji se sastoji od mešavine zemljišta i cementa i zemljišta koje je podložno brzom sabijanju. Drugi pristup podrazumeva mat fundamente postavljene na relativno tankom osnovnom sloju mešavine zemljišta i cementa, koji je dopunjen strateški postavljenim dubokim stubovima sa mešavinom zemljišta. Oba ova pristupa obezbeđuju strukturnu pouzdanost silosa, zalažu se za primenu metoda unapređenja zemljišta koji su lako dostupni na bugarskom tržištu i nude brzo i efikasno izvođenje.

Ključne reči: *les, sklopivo tlo, plitki temelj, poboljšanje tla, silos, brzo sabijanje, mešanje cementa i tla, duboko mešanje tla*

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Review paper

COMPARISON OF DEMS GENERATED USING DIFFERENT DATA SOURCES AT A MOUNTAIN SITE

UDC 528.4:004

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Abstract. *The paper analyzes digital elevation models (DEM) of the same area based on different sources and methods of geospatial data collection. An open-source DEM was created in the mountainous area of Colus County, which is the northern part of the US state of California. At the same time, the data on terrain elevation refer to LiDAR surveys and the content of topographic maps, while ASTER data are based on ellipsoidal heights. Also, the source data contain a certain error of the chosen collection method and the processing process itself, as well as errors related to mutual deviations of the height reference systems. Ignoring the height system, it is observed that the error of the data source significantly affects the quality of the model display as well as the terrain details. The display of DEM based on LiDAR data is very close to DEM based on data from topographic maps, in contrast to the elevation model obtained based on ASTER images.*

Key words: *quality comparison, DEM, different data sources, same area.*

1. INTRODUCTION

The development of new techniques and technologies is accelerating the process of collecting and modeling geospatial data, and thus improving the quality of digital elevation models (DEMs) visualization. In recent years, there have been two fundamental advancements. On one hand, modern techniques such as LiDAR (Light Detection and Ranging) determine elevation through direct distance measurements, providing much greater accuracy in determining elevation. On the other hand, there is the ability to

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generate global DEMs. For example, SRTM (Shuttle Radar Topography Mission), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), and similar technologies offer the capability to create DEMs with great ease and precision [1].

DEM products have applications in a wide range of disciplines, including civil engineering, hydrology, geomorphology, environmental protection, forestry, and more. Some of their applications include modeling for natural disaster prevention (such as floods and fires), soil erosion, weather forecasting, climate change, etc. Additionally, DEMs are considered a global fundamental topic in United Nations geospatial data. Therefore, one of the basic premises is the need for DEMs to have sufficient quality to meet the requirements of many applications [2].

Many times, it can be the case that a DEM with a certain level of quality is used in a study that requires a different level of quality. Specifically, two scenarios can occur. First, a higher-resolution and more accurate DEM may be used than what the study's requirements dictate, leading to an overutilization of DEM capabilities and the consumption of additional resources (e.g., memory and disk space, computation time, etc.). Second, an insufficiently detailed and accurate DEM may be employed for the study's needs, resulting in a study that produces inaccurate results, potentially leading to incorrect conclusions. To address this issue, users need to understand the quality of the DEM [2].

2. Methods and Technologies for Representing DEMs

DEMs are a specific case of interpolated continuous surfaces. Variations in the elevation of an area's surface can be modeled in several ways. DEMs can be represented as mathematically defined surfaces, as point or linear images. Linear data can be used to represent contour lines and profiles, as well as critical features such as streams, ridges, coastlines, and slope breaks. In geographic information systems (GIS), DEMs are modeled as regular grids (elevation matrices) or irregular triangulated networks (TINs). These two forms can be transformed into each other, and the choice depends on the type of data analysis required [14].

For continuous fields, there are two main ways of representing spatial data. The first is Delaunay triangulation, i.e., TIN (Triangular Irregular Network) digital elevation modeling, and the second, which is more commonly used, is an elevation matrix or grid, employed in raster-based GIS and image analysis. Delaunay's networks are often used independently of GIS to support finite element modeling of dynamic processes like groundwater flow, flooding in flood-prone areas, or air quality.

Elevation matrices are the most common form of discretized elevation surfaces. They were originally derived from quantitative stereoscopic measurements on aerial photographs. Today, there are modern ways of collecting elevation data. In particular, many experiences show that LiDAR technology and remote sensing efficiently replace conventional techniques and methods for gathering geospatial data, such as digitizing topographic maps and aerial photogrammetry. The subject of this work is elevation models, comparing DEMs obtained from different data sources, all in an effort to determine the quality of modern and conventional data collection and modeling technologies. Elevation models are created based on data collected from LiDAR technology, data obtained from remote sensing, and data digitized from topographic maps.

The paradigm of continuous (uninterrupted) fields provides a rich basis for spatial modeling, especially when data is stored in regular square grids. Mathematical operations on continuous fields can be divided into point and spatial operations. Point operations are the same as those performed in spatial operations of geographic entities, where the point is one of the basic geographic primitives. Spatial operations include spatial filtering, surface derivative calculations, slope, aspect, curvature, surface topology and drainage network analysis, spatial proximity, linear and non-linear closeness, and properties of the entire surface, such as line of sight and terrain exposure.

The most commonly used continuous field is the digital elevation model, as was the case in this study. Analyzing the attributes it carries can yield a large amount of new data. However, these operators can be equally well applied to any continuous field, such as remote sensing imagery or the results of interpolation and spatial modeling. Table 2 provides an overview of attributes that can be calculated from DEMs, as well as possible applications of these attributes [14].

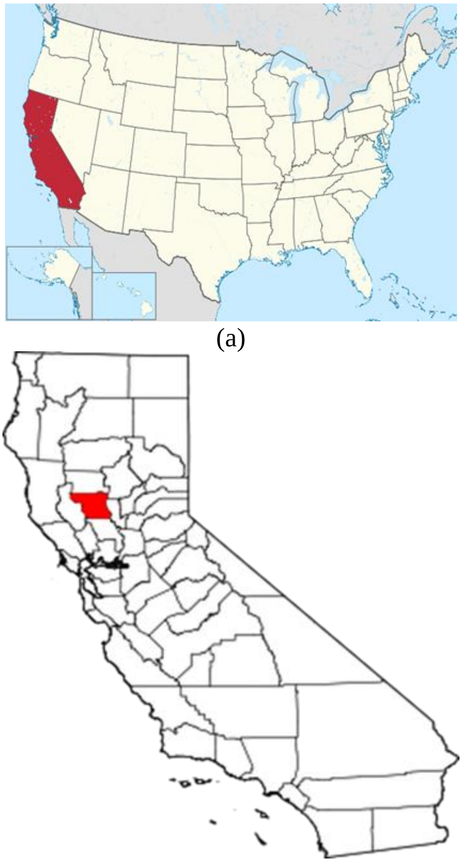
Table 1 Overview of attributes that can be calculated from DMV and its applications

Attribute	Definition	Application
Height	Height above sea level or local reference	Determining potential energy; climate changes – pressure, temperature, vegetation and soil trends, material volume, embankment and cut calculations
Slope	Rate of altitude change	Slope of the terrain, aboveground and underground flows, land capability classification, vegetation types, resistance to upstream transport, remote sensing image correction
Aspect	Azimuth of the steepest descent	Sunlight exposure, Evaporation, Vegetation attributes, Correction of remote sensing images
Profile curvature	Rate of change in land slope	River flow acceleration, areas of increased erosion, sedimentation, vegetation, valuation indices
Horizontal curvature	Rate of change in aspect	Convergence and divergence of flow, soil moisture properties
Local drainage direction	Direction of the steepest descending flow	Calculating watershed attributes based on flow topology, estimating lateral material transport along locally defined networks
Upstream elements/Areas/Specific catchment areas	Number of cells/areas upstream of a given cell/upstream area per unit contour line width	Watershed areas upstream of a given location, in case of outlet, the entire watershed area, volume of material exiting the watershed
Length of the flow	Length of the longest path along the LDD upstream of the given cell	Flow acceleration, erosion rate, sediment quantity
Flow channel	Cells with flowing water/cells with more than predefined upstream elements	Flow intensity, flow location, erosion, and sedimentation
Ridge	Cells without upstream areas	Watersheds, vegetation research, soil, erosion, geological analysis, connectivity
Moisture indices	Specific catchment area and slope	Moisture retention index
Stream power index	Specific catchment area and slope	Measure of the erosive power of overland flow
Sediment transport index	$(n+1)(\frac{A_s}{22.13})^n(\frac{\sin\beta}{0.0896})^m$	Characterizes erosion and deposition processes
Watershed length	Distance from the highest point to the outlet	Reduction of overland flow
Line of sight	Areas of mutual visibility	Locating microwave transmitters, fire monitoring stations, hotels, military applications
Sunlight exposure	Amount of solar energy received per unit area	Vegetation and soil research, evaporation, energy-efficient building locations, terrain shading

3. PROCEDURES AND RESULTS

3.1. Area of interest

The area of interest in this study is a selected part of a mountainous region in Colusa County, Northern California (Figure 1), located at approximately 39° 7' 18" North latitude and 122° 20' 10" West longitude.



(a)

(b)

Fig. 1 California State (a) and Colusa County (b) Territory [2]

The surface where elevation models were formed covers an area of approximately 10,000 square meters, with dimensions of 1000m x 1000m. Google Earth data can be viewed and shared using Keyhole Markup Language (KML) files (Figure 2).

Three elevation models were created in this area. The first model was generated using airborne laser scanning. The second elevation model was obtained from ASTER satellite sensors, and the third elevation model was derived from digitizing existing topographic maps. All data was georeferenced in the UTM zone 10 N projection.

Fig. 2 Mountain Research Site [2]

3.2. Formation of DEMs based on LiDAR data

Data collection and processing were carried out by the National Center for Airborne Laser Mapping (NCALM) in 2017, using a scanner attached to an aircraft that recorded data at a density of 626 points per square meter. The data were downloaded from the Open Topography website and classified into three classes: Class 2 - Ground, Class 9 - Water, and Class 1 - Unclassified, encompassing everything above the Ground class, i.e., the terrain. This includes low, medium, and high vegetation depending on the landscape. Only the Ground class was used for creating the DEM, so no additional classification was needed.

Given the large number of recorded points (over 69 million), it was necessary to select software capable of handling a significant amount of data efficiently. Considering the required computational performance and desired features, MicroStation V8i software, developed by Bentley Systems, proved to be an effective solution. The primary data format is DGN, but various data types, including raster data like TIFF and GeoTIFF, can be imported and exported, which is essential for DEM creation, subsequent analysis, and comparisons.

The applications TerraScan, TerraModeler, and TerraPhoto were also used, all of which are compatible with Bentley Systems products. One of their advantages is their user-friendly interface, fully integrated into MicroStation, making data management much more straightforward.

Before loading the point clouds, it was necessary to configure the coordinate system, i.e., the coordinate system range in which the point cloud is located. To determine the necessary coordinate system parameters, appropriate tools from the application group had to be selected, and after specifying the location, a point cloud file was chosen. By further selecting options and processing, the DEM in its original form was obtained (Figure 3).

For displaying the DEM, options providing a hypsometric representation of the terrain were used (Figure4). These options simultaneously combine the elevation and slope of the terrain represented in the form of triangles. The HSV (Hue - Saturation - Value) principle is used, where elevation is shown by color and the slope of the terrain by the shade of that color. Furthermore, the illumination of triangles represents sunlight exposure.

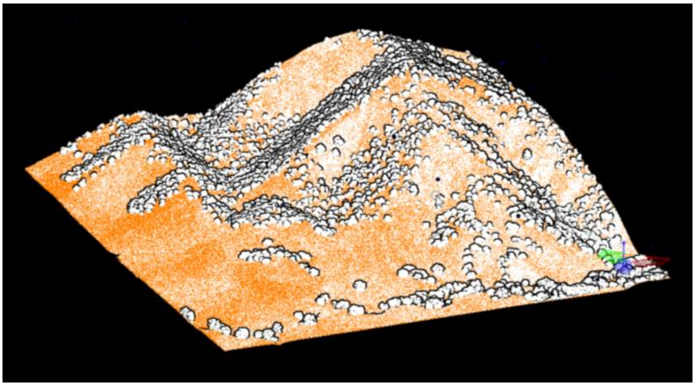


Fig. 3 LiDAR Data in Original Form

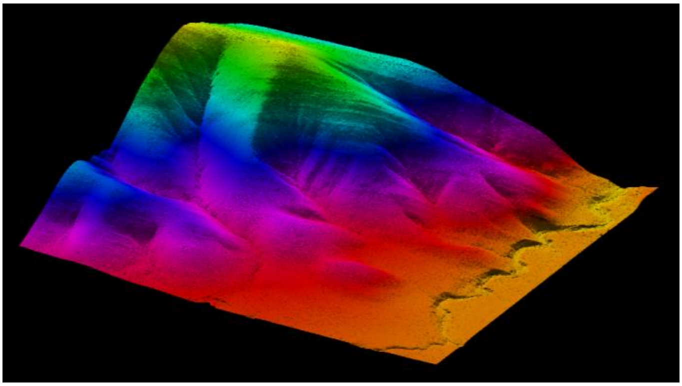


Fig. 4 Hypsometric Representation of Terrain

For further analysis, the final DEM model is exported as a raster image, lattice, or xyz file to make it usable for comparisons and quality assessment with other models of the same area obtained by different techniques.

After exporting the DEM as a raster image, a range of values from 0 to 255 is obtained for each pixel (Figure 5). Each pixel contains elevation data, which will be used in the next step to create a model. Based on this, it can be concluded that black pixels represent lower elevations, while white pixels are reserved for displaying higher elevations. The shades of white and black pixels proportionally represent the difference in elevations.

Subsequently, tools from the ArcGIS software environment were used. Based on the previously exported DEM in the form of a raster image from MicroStation, a DEM was created in the ArcMap program. The display of the model was initiated and realized in the ArcScene program (Figure 6).

The created elevation model has a dynamic form, meaning that any changes in point classification are reflected in the final representation of elevations and geomorphological features of the terrain. The Ground class, from which the DEM in TIN structure was created, was chosen as the final DEM and was subsequently used as one of the three elevation models for analysis and comparison in further research.

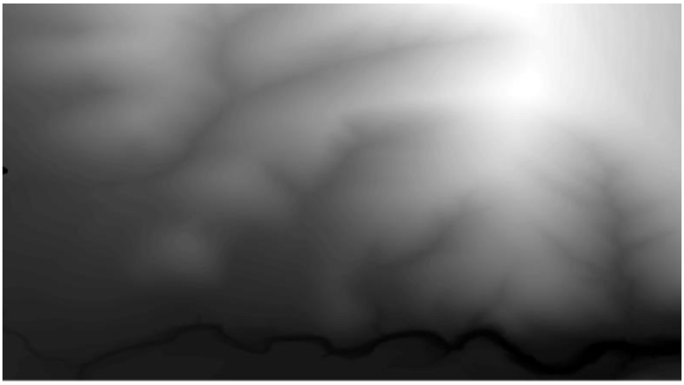


Fig. 5 Exported DEM Generated from LiDAR Data

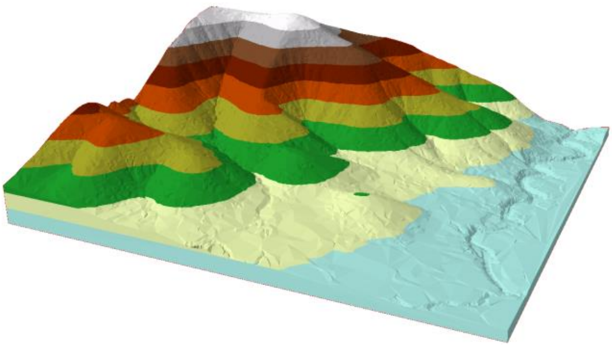


Fig. 6 Formed DEM Based on LiDAR Data in TIN Structure

3.3. Creating a Digital Elevation Model (DEM) based on satellite imagery

A satellite image for the same area was obtained by the Terra satellite [7], specifically using its ASTER sensor, during the period from March 1, 2000, to November 30, 2013. The image has a spatial resolution of 30 meters and has been automatically set to the Universal Transverse Mercator (UTM) 10N zone cartographic projection. The downloaded image covers a much larger area than the research area or the area covered by LiDAR data. The area covered by the LiDAR data is taken as the reference for the research area. Specifically, a portion of approximately 10,000 square meters has been extracted and aligns with the area covered by the LiDAR data. The area of interest is depicted as a rectangle in Figure 7.

A raster image of the desired area was obtained from the ASTER image, and using the same tool as in the case of LiDAR data, "Raster to TIN," a new Digital Elevation Model (DEM) in TIN (Triangulated Irregular Network) structure was created (Figure 8).

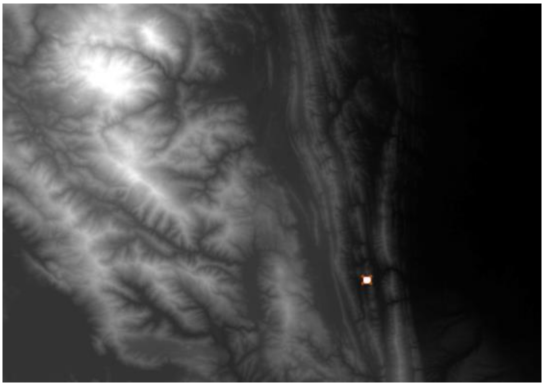


Fig. 7 The area of interest on the ASTER image

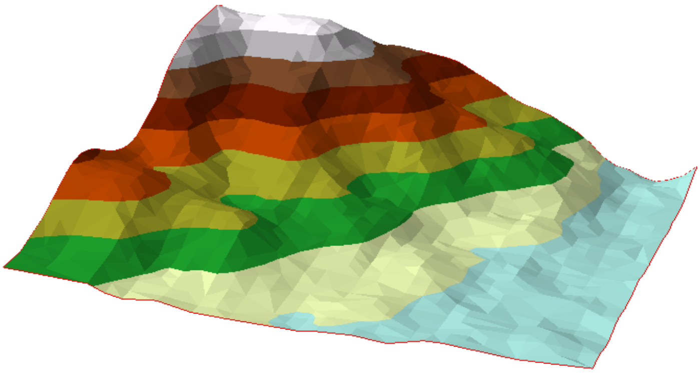


Fig. 8 The generated DEM based on ASTER data in TIN (Triangulated Irregular Network) structure

3.4. Creating a Digital Elevation Model (DEM) through the digitization of a topographic map

The topographic map for the area of interest was downloaded from the website ngmdb.usgs.gov [8]. The key characteristics of the topographic map are (Figure 9):

Publication date: 1958
Map scale: 1:24,000
Cartographic projection: UTM, Zone 10
Measurement unit: feet
Contour interval: 40 feet, equivalent to 12.19 meters.

The downloaded topographic map has been georeferenced into a projected coordinate system. Subsequently, the contours representing the terrain's elevation were vectorized.

In the next step, the Shapefile with contours was loaded into ArcMap, and by using the "Create TIN" option within "3D Analyst Tools" under "Data Management," a Digital Elevation Model (DEM) in TIN (Triangulated Irregular Network) structure was generated (Figure 10).

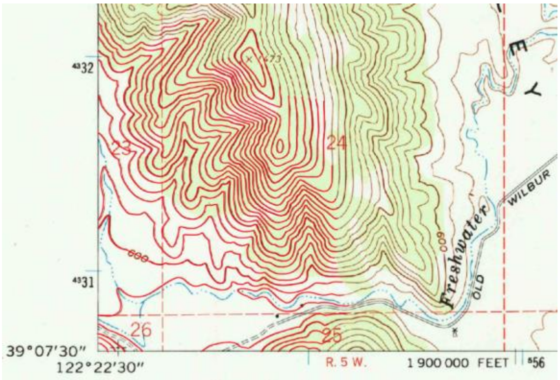


Fig. 9 Quasi-static tests of Model M1: a) Shot during the quasi-static testing of column Model M1; b) Damage from quasi static testing of column Model M1

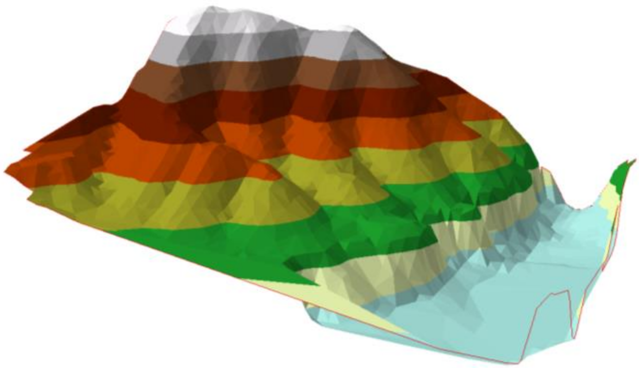


Fig. 10 The generated DEM based on the topographic map in TIN (Triangulated Irregular Network) structure

4. Analysis and Discussion of Results

After creating a Digital Elevation Model (DEM) based on various data sources for the same research area, the analysis and comparison of the obtained elevation models were conducted. The comparison and analysis of the DEMs were carried out as follows:

- Creating and performing a comparative analysis of cross-sectional profiles.
- Generating and visualizing elevation differences between models.
- Creating and displaying viewpoints.

Comparisons and analyses were conducted within the ArcGIS software environment.

4.1. Analysis of cross-sectional profiles on Formed Elevation Models

Creating cross-sectional profiles can be done at various locations on the generated elevation models from different data sources. The analysis of cross-sectional profiles was performed at characteristic points and directions within the model. Two characteristic profiles were created. The first profile was created at the summit of a mountain, where significant elevation changes occur (Figure 11).

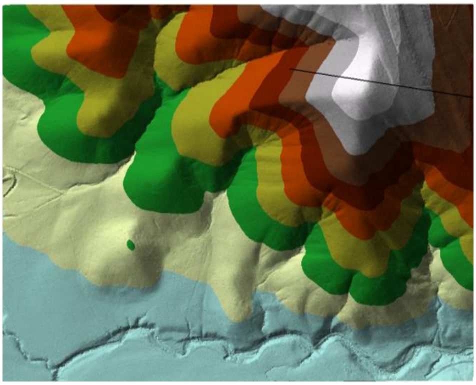


Fig. 11 Location of the first profile

By plotting profiles along the generated elevation models, specific cross-sections are obtained, along with graphical representations and numerical information about them. In Figure 12, individual profile views are provided. In these views, certain discrepancies or differences between the DEMs obtained from different data sources can be observed.

The green line represents the DEM obtained from topographic maps. For instance, it shows a certain flattening at the location of the mountain summit. In this case, the contour interval is not always well chosen to accurately represent certain geomorphological features, especially the terrain peaks. Some parts of the terrain are not suitable for displaying and using new contour intervals, which is why the summit appears "flattened," which is not the case in nature.

The red line represents the elevation model obtained through LiDAR technology. In areas with a constant slope, there are no significant deviations, especially when compared to the green line (vectorized topographic maps).

This primarily applies to the left side of the graph since the geomorphology of the terrain on the left slope is quite uniform. However, there are more significant deviations on the right side. The terrain is slightly "undulating," and this could not be accurately represented by contour lines, unlike LiDAR data, which have high density. The most significant differences are observed at the mountain's summit, for the previously mentioned reasons and explanations.

The blue line represents the elevation model created based on ASTER data. In terms of intensity, it is very similar to the DEM obtained from LiDAR data. It closely follows the terrain, with no major deviations compared to the previous two models. However, it is important to note that in this case, the DEM represents ellipsoidal heights, not orthometric heights, leading to relative differences in elevations. Such systematic differences can be removed by calibrating the model to known control points using first or second order polynomials [13]. Besides this difference, there is a somewhat better match between ASTER and LiDAR data on the right side of the slope, as there is a convergence of ellipsoid and geoid heights in that area (Figure 13).

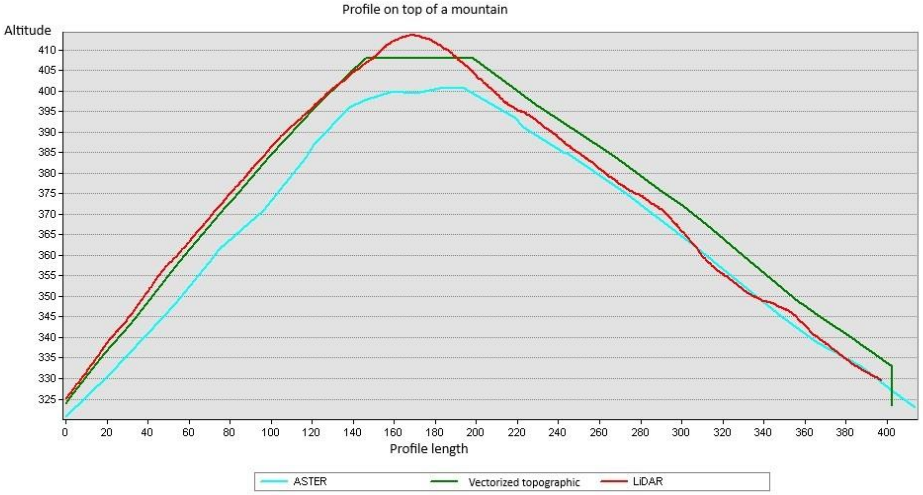


Fig. 12 Graphs of the first profile

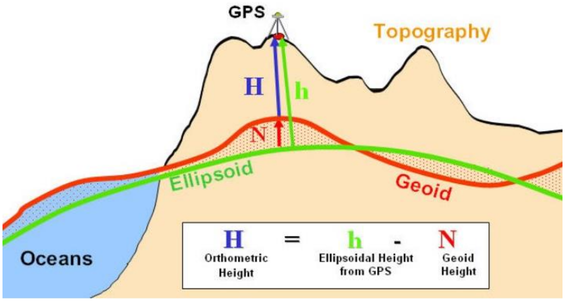


Fig. 13 Difference between ellipsoidal and orthometric height [9]

The second characteristic cross-sectional profile was projected and drawn across the middle of the mountain, crossing several mountain passes (Figure 14).

The second profile graph yielded more complex results compared to the first profile. The DEM created from LiDAR data provides a more detailed representation of the terrain, especially in the areas of local minima (valleys) and maxima (peaks). It also offers a truer approximation of the terrain compared to the DEM formed by vectorizing contour lines from topographic maps (Figure 15). When it comes to the DEM obtained from ASTER data, it presents the terrain quite faithfully and offers a good approximation of geomorphological features unless systemic deviations due to ellipsoidal and orthometric heights are ignored. However, the issue with the DEM created from ASTER data is that due to the image resolution, it cannot detect minor geomorphological changes, which can be observed on the second (right) local minimum (Figure 15). Therefore, the DEM created from LiDAR data reveals many details compared to DEMs formed by vectorizing topographic maps or using ASTER data.

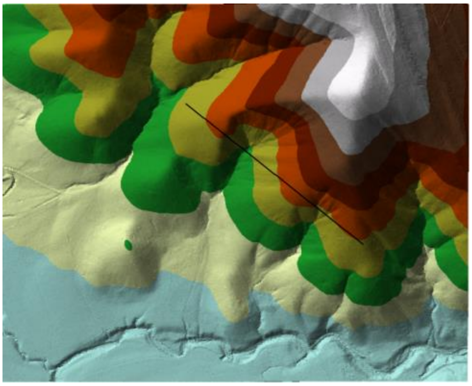


Fig. 14 Location of the second profile

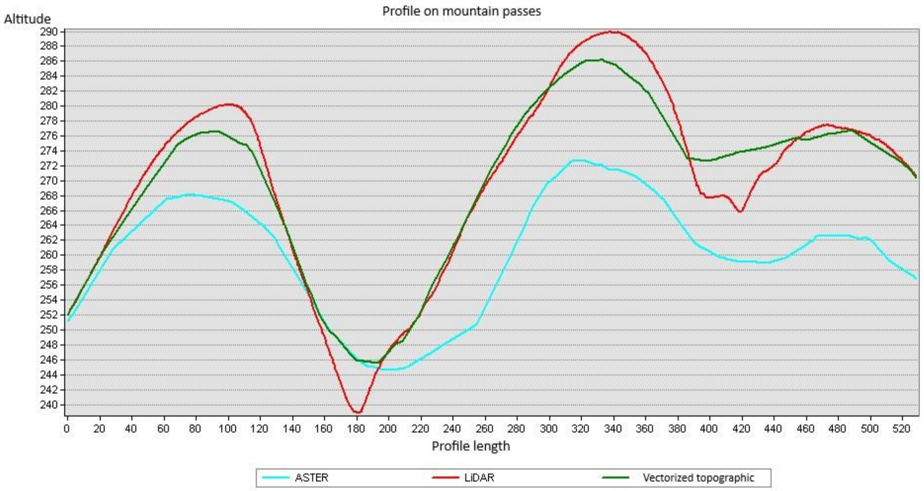


Fig. 15 DEM Profiles Graphs

4.2. Difference in elevation between obtained DEMs

After generating DEMs for the same area from various data sources, a geometric comparison of the elevation models was performed, specifically the triangles of the input surfaces of the DEMs. To clarify, the DEM triangles based on LiDAR data should be classified if their entire surface is below or above the DEM obtained from vectorized topographic maps. In cases where intersections occur between certain triangles of the

LiDAR-based DEM and the triangles of the DEM based on vectorized topographic maps, the existing triangles are divided into smaller ones. In this manner, the new triangles are entirely either above or below the surface of the other model and are classified accordingly. Adjacent triangles, if classified in the same way, are merged into corresponding polygons. The volumes of the triangles (the volume above or below the reference surface) and their surface areas are summed up, providing a better overview of the areas that are above and below the reference model. As a result, the output presents the content with previously defined and classified polygons along with their volume and surface area values. The difference surface is constructed using Delaunay triangulation criteria [10].

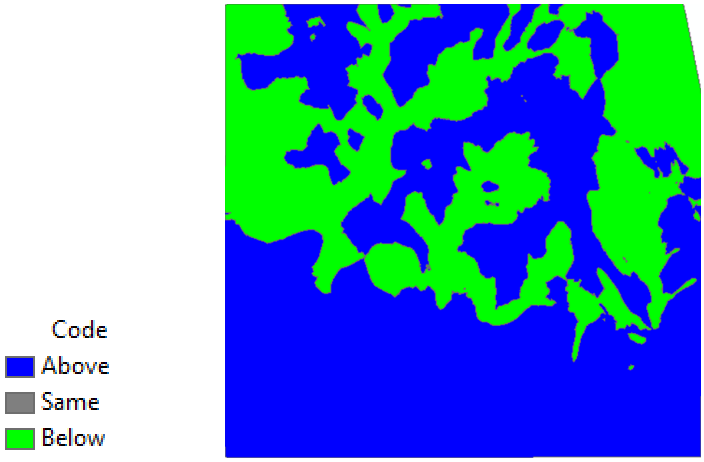


Fig. 16 Elevation difference between LiDAR-Based DEM and vectorized topographic map

In Figure 16, it is evident that the LiDAR-based model is consistently above at locations of local maxima and below at locations of local minima because it provides a more detailed representation of valleys and peaks compared to contour lines. This aligns with the previous analysis in Figure 15. In the lower part of Figure 16, there is a slight difference in elevations, and the terrain is predominantly flat. The DEM created based on contour lines could not accurately represent this area, resulting in the entire model consistently being below the LiDAR-based DEM. The elevation comparison is limited to the LiDAR model and the topographic map model, as the ASTER model was excluded due to constant differences in elevations.

4.3. Calculation and line of sight analysis on elevation models

Comparative analysis that can be conducted when DEMs are available pertains to line of sight calculations. The initial step involves placing a point on the DEM, from which line of sight calculations are performed to obtain the corresponding line of sight area. Specifically, using the "Viewshed 2<Visibility<3D Analyst Tools" option yields a raster image of the visible portion of the model from the designated point. Combining the resulting rasters with the model provides the results depicted in Figure 17.

The point from which the line of sight was calculated is in the same position on all three models (Figure 17). The line of sight position is set on the top of a hill, slightly shifted to the west. It can be said that visibility on the models is similar, with the clearest definition on the LiDAR-based DEM (Figure 17, a). On the right are the DEMs obtained from the topographic map and satellite image, yielding similar results but with less precision. The primary reason for this difference lies in the quality and accuracy of data collection methods.

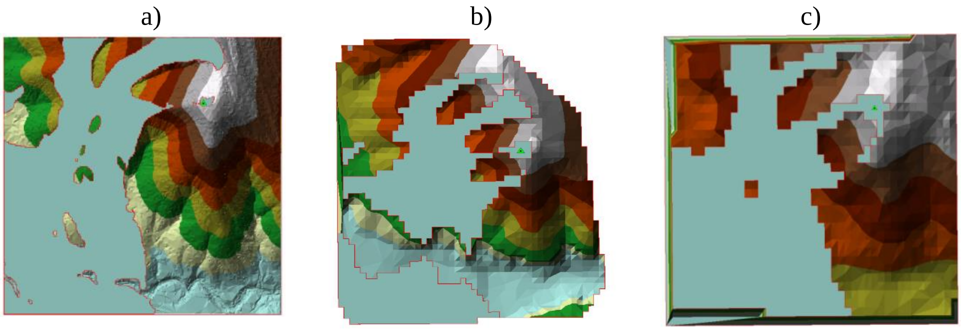


Fig. 17 Line of Sight Calculation with DEMs: a) LiDAR data; b) topographic map; c) ASTER image

The calculation and analysis of the line of sight have significant relevance and applications in the design of geodetic point networks, road design, power lines, and similar infrastructure projects. This capability enables visibility determination without the need for on-site visits, providing a substantial advantage and efficiency when working in such inaccessible terrains.

5. Conclusions

Once all three elevation models have been obtained, loaded into the software, and spatially aligned, analyses and comparisons were conducted using the following methods: creating profiles at characteristic locations, analyzing the elevation differences between models through their spatial overlay, and performing a line of sight analysis from the same point on all three models. Whether a particular area's surveying was conducted using older, conventional methods or more modern techniques, there is always an effort to produce a more faithful digital representation of the terrain. From topographic maps that only offered a 2D representation, advancements in data acquisition instruments and computational data processing are apparent, showing significant differences in accuracy and visual representation. Modern surveying methods and existing GIS software allow the creation of 3D models of mountains, roads, tunnels, buildings, and even their interiors, producing precise, accurate, and credible representations that anyone can easily understand and review.

By analyzing the three DEMs created using different methods in this study, it can be observed that it is possible to create quality elevation models both with conventional and newer surveying methods. Depending on resources, purposes, and required accuracy, elevation models can be created even from topographic maps that were made 50 or even 100 years ago. The quality of these models primarily depends on scale, contour intervals, local and global deformations that occurred before and during the digitization process. New surveying methods now dominate due to the pursuit of a more precise and faithful terrain representation, offering numerous advantages over traditional topographic maps.

The main drawback of newer methods lies in their cost, which is higher than digitizing and processing existing topographic maps.

From the analysis of the obtained results, it can be concluded that LiDAR surveying provides the best and most accurate surveying results. It is apparent in the lower part of the topographic map that a river is depicted, but only in the LiDAR elevation model is this river observable. Its width, depth, or the volume of the riverbed can be accurately calculated. In contrast, the other two models do not allow for the identification of the riverbed. Creating a model from vectorized topographic maps is suitable for areas where a high level of model accuracy is not required. Its advantage, unlike the other two methods, is that it does not require additional time for surveys and investment in data acquisition. Accurate topographic maps for that area are needed. The advantage of digital models obtained from satellite images is that they do not require on-site surveys or additional time for topographic map digitization. For an artificial satellite, every part of the Earth is visible, and surveying data can be obtained independently of the region's inaccessibility, unlike other surveying methods. One satellite image covers a much larger area than a map and is ideal for mapping vast regions. The drawback compared to other surveying methods is the spatial resolution, but with the ongoing trend of increasing satellite image resolution, their more frequent application is expected.

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REFERENCES

1. Mesa-Mingorance, J.L.; Chicaiza-Mora, E.G.Bueaño, X.; Cai, J.; Rodríguez-Pascual, A.F.; Ariza-López, F.J. Analysis of Users and Uses of DEMs in Spain. Int. J. Geo-Inf. 2017, 6, 406. [CrossRef]
2. José L. Mesa-Mingorance and Francisco J. Ariza-López: Accuracy Assessment of Digital Elevation Models (DEMs): A Critical Review of Practices of the Past Three Decades, Remote Sens. 2020, 12, 2630; doi:10.3390/rs12162630
3. Retrieved from: https://sr.wikipedia.org/sr-ec/Kalifornija
4. Retrieved from: https://en.wikipedia.org/wiki/MicroStation
5. Retrieved from: https://www.terrasolid.com/products
6. TerraModeler User’s Guide (1995-2016)
7. Retrieved from: https://www.esri.com/content/dam/esrisites/sr-rs/media/pdf/implementation-guides/implement-arcgis-online.pdf
8. Retrieved from: https://www.nasa.gov/mission_pages/terra/spacecraft/index.html.
9. Retrieved from: https://ngmdb.usgs.gov
10. Retrieved from: https://www.esri.com/content/dam/esrisites/sr-rs/media/pdf/implementation-guides/implement-arcgis-online.pdf
11. Retrieved from: https://www.researchgate.net/figure/Orthometric-geoid-and-ellipsoid-heights-Ellipsoidal-Orthometric-N-h-H-1_fig1_329686559
12. Retrieved from: https://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/how-surface-difference-3d-analyst-works.htm
13. Bulatović, V., Sušić, Z., Ninkov, T. (2012): Estimate of the ASTER-GDEM regional systematic errors and their removal, International Journal of Remote Sensing, Volume 33, Issue 18, pp. 5915-5926, https://doi.org/10.1080/01431161.2012.676744
14. Borrough, P.A.; McDonnenell, R.A.; „Principles of Geographical Information Sistems“ 2e, Principi Geografskih informacionih Sistema, drugo izdanje, prevod objavljen 2006. Građevinski fakultet Univerziteta Beograd; ISBN 86-7518-070-5; COBISS.SR-ID 131291916.

POREĐENJE DIGITALNIH ELEVACIONIH MODELA PLANINSKOG TERENA KREIRANIH KORIŠĆENJEM RAZLIČITIH IZVORA PODATAKA

U radu se analiziraju digitalni elevacioni modeli (DEM) istog područja na osnovu različitih izvora i metoda prikupljanja geoprostornih podataka. DEM otvorenog koda kreiran je u planinskom području okruga Kolus, koji je severni deo američke države Kalifornije. Istovremeno, podaci o nadmorskoj visini terena odnose se na LiDAR snimanja i sadržaj topografskih karata, dok se ASTER podaci zasnivaju na elipsoidnim visinama. Takođe, izvorni podaci sadrže izvesnu grešku izabranog načina prikupljanja i samog procesa obrade, kao i greške koje se odnose na međusobna odstupanja visinskih referentnih sistema. Zanemarujući visinski sistem, primećuje se da greška izvora podataka značajno utiče na kvalitet prikaza modela kao i na detalje terena. Prikaz DEM-a na osnovu LiDAR podataka je veoma blizak DEM-u na osnovu podataka sa topografskih karata, za razliku od modela nadmorske visine dobijenog na osnovu ASTER slika

Ključne reči: *Poređenje kvaliteta, DEM, različiti izvori podataka, ista oblast.*

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