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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).

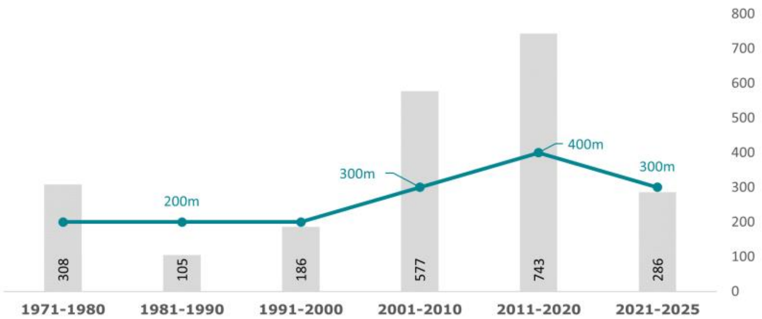

Fig. 1 The construction of high-rise buildings in Europe according to the period of construction and the maximum height achieved

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).

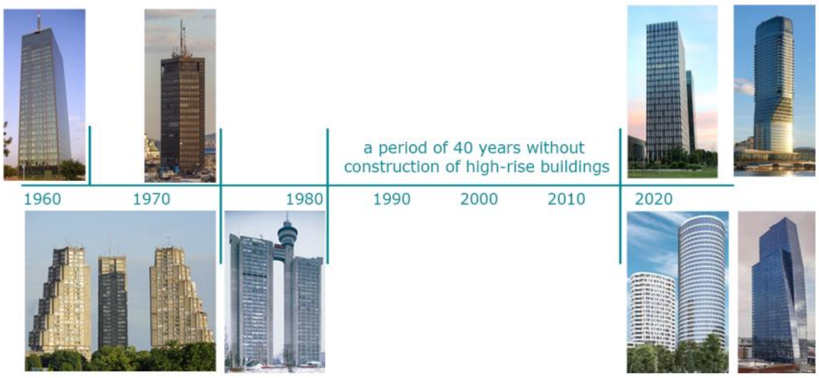

Fig. 2 High-rise buildings in Belgrade

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.

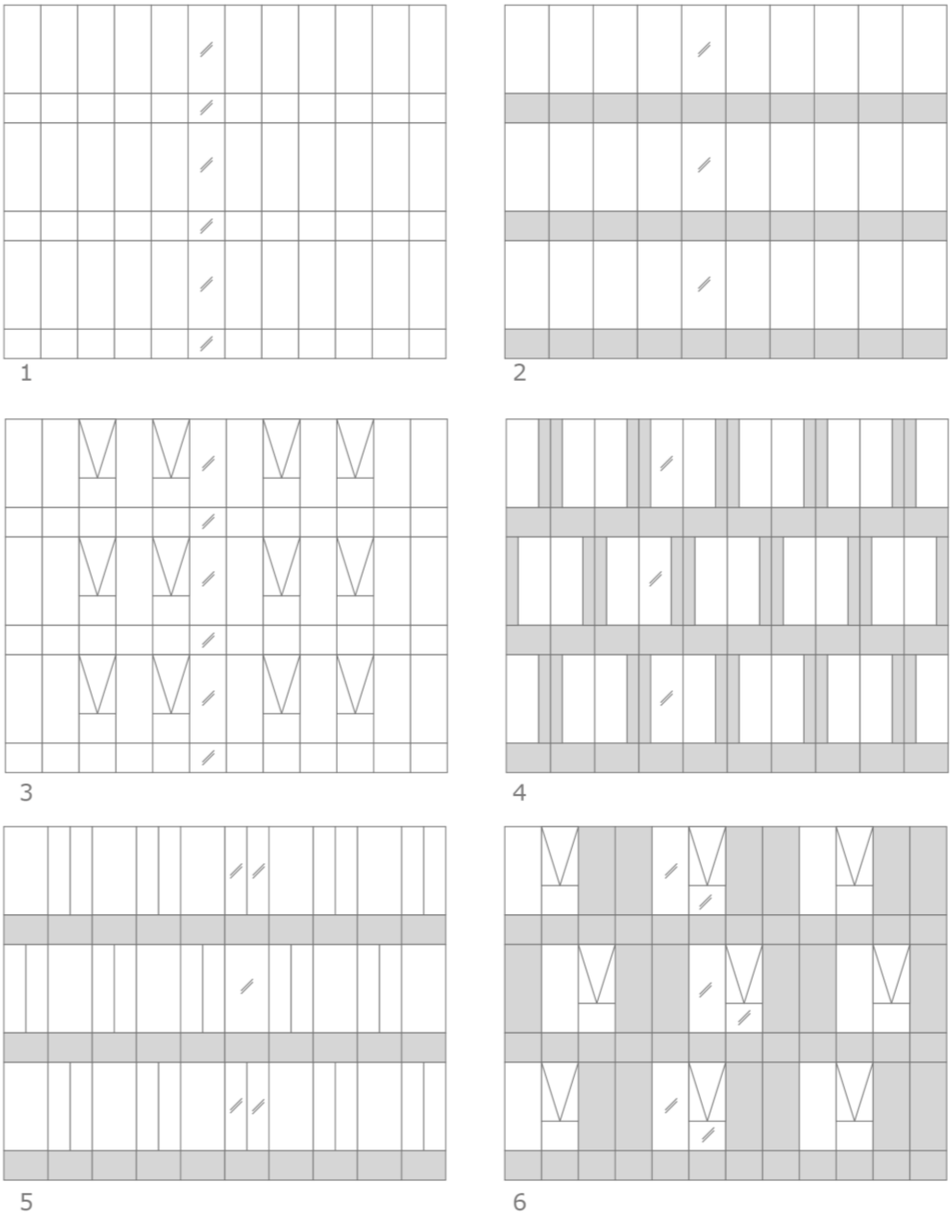

Fig. 4 Defined base models of façade segments for numerical assessment of circularity potential

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.

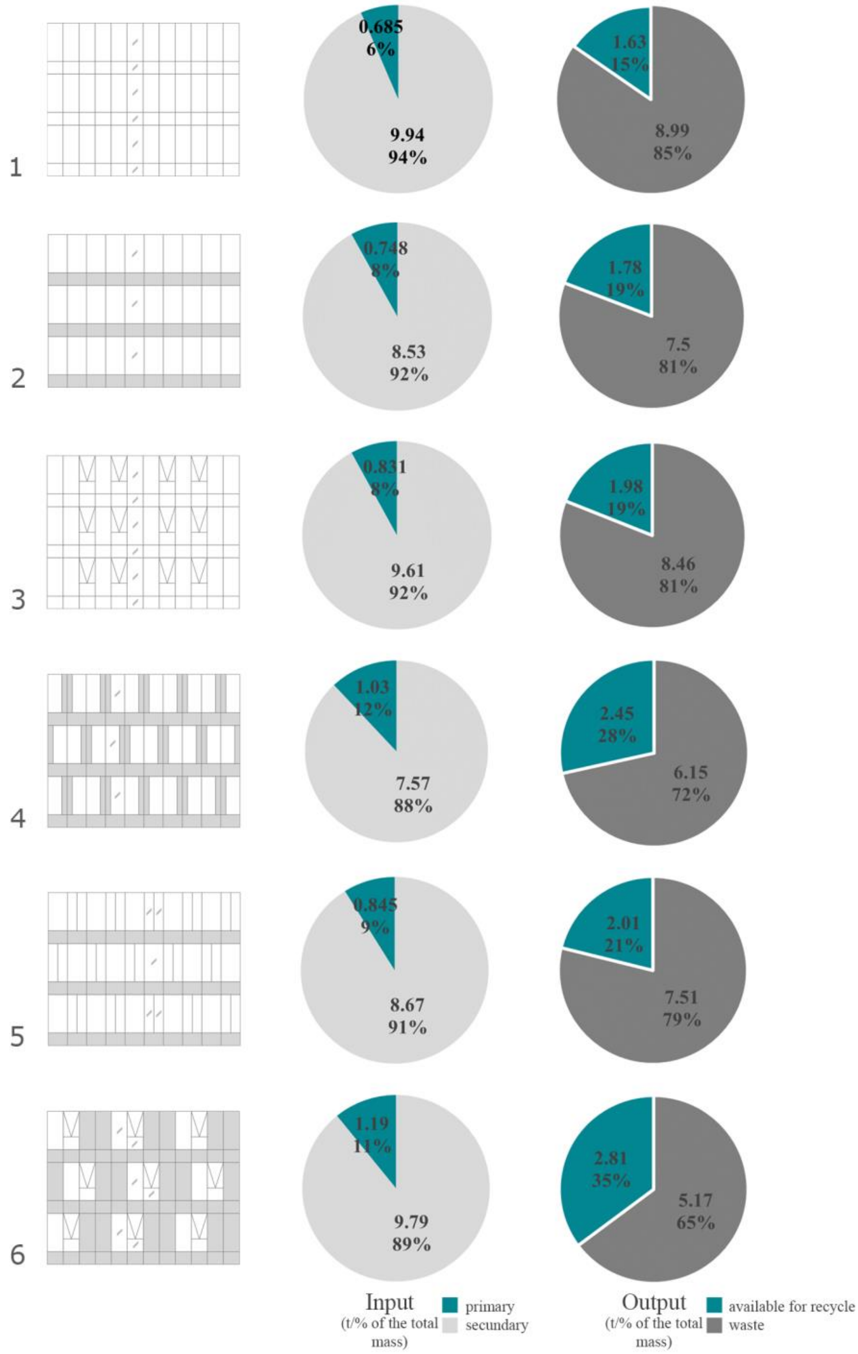

Fig. 5 Input and output flows of materials for façade models 1-6

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.

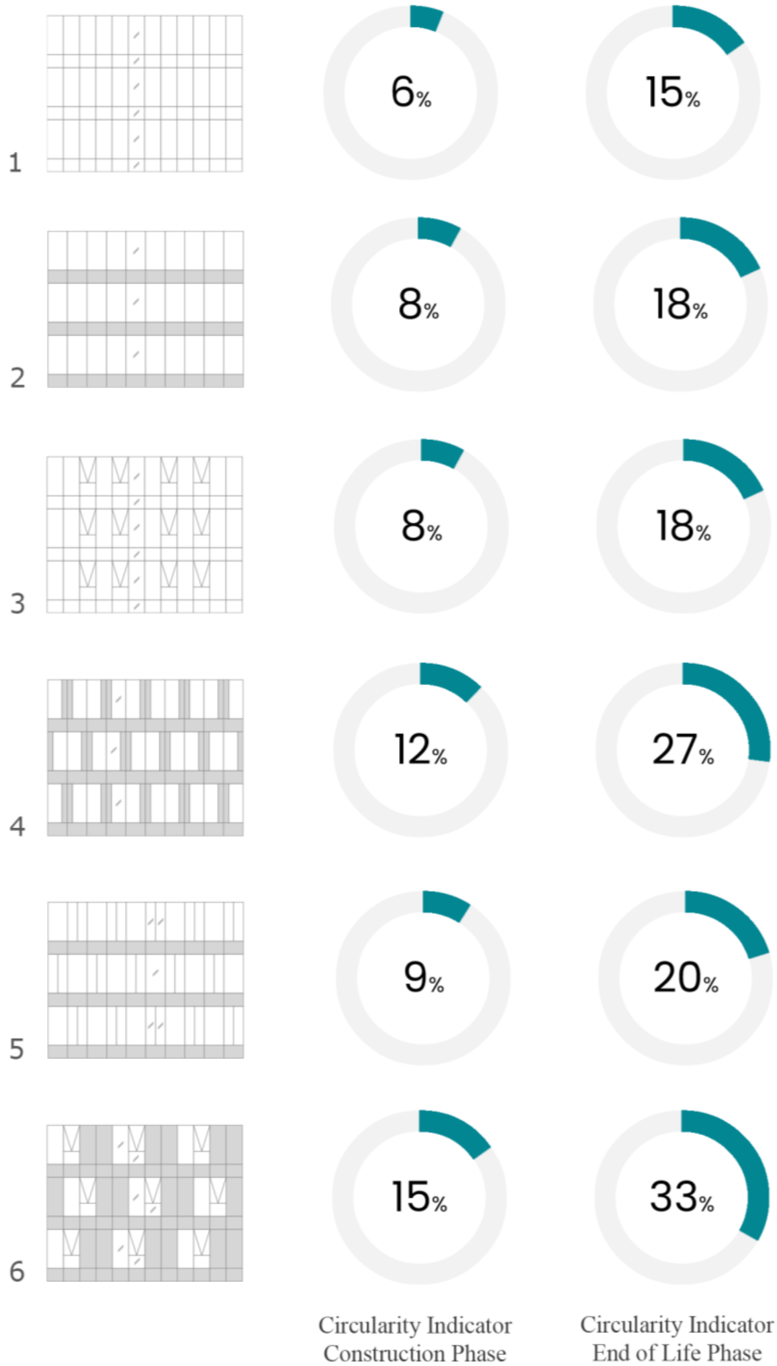

Fig. 6 Circularity indicator for the Construction and End of Life Phase for façade segments of base models 1-6

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.

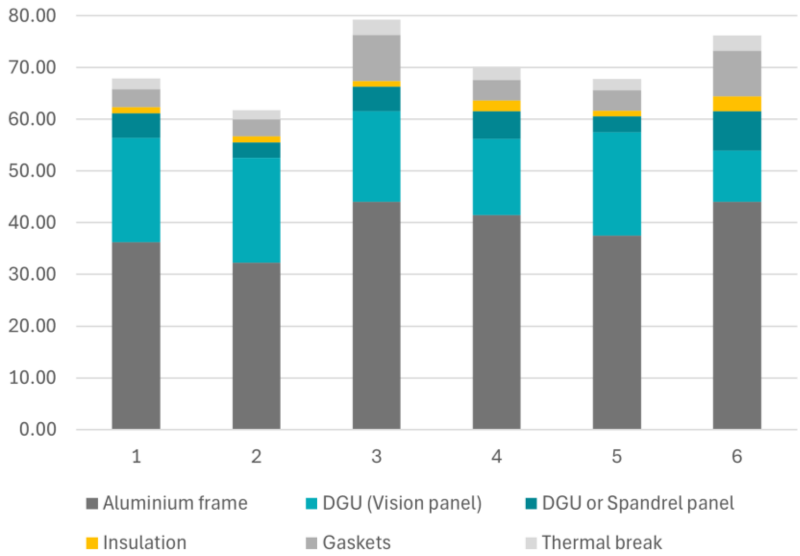

Fig. 7 Overview of the contribution of individual components to the total CO_2 emission of façade segments (models 1-6)

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).

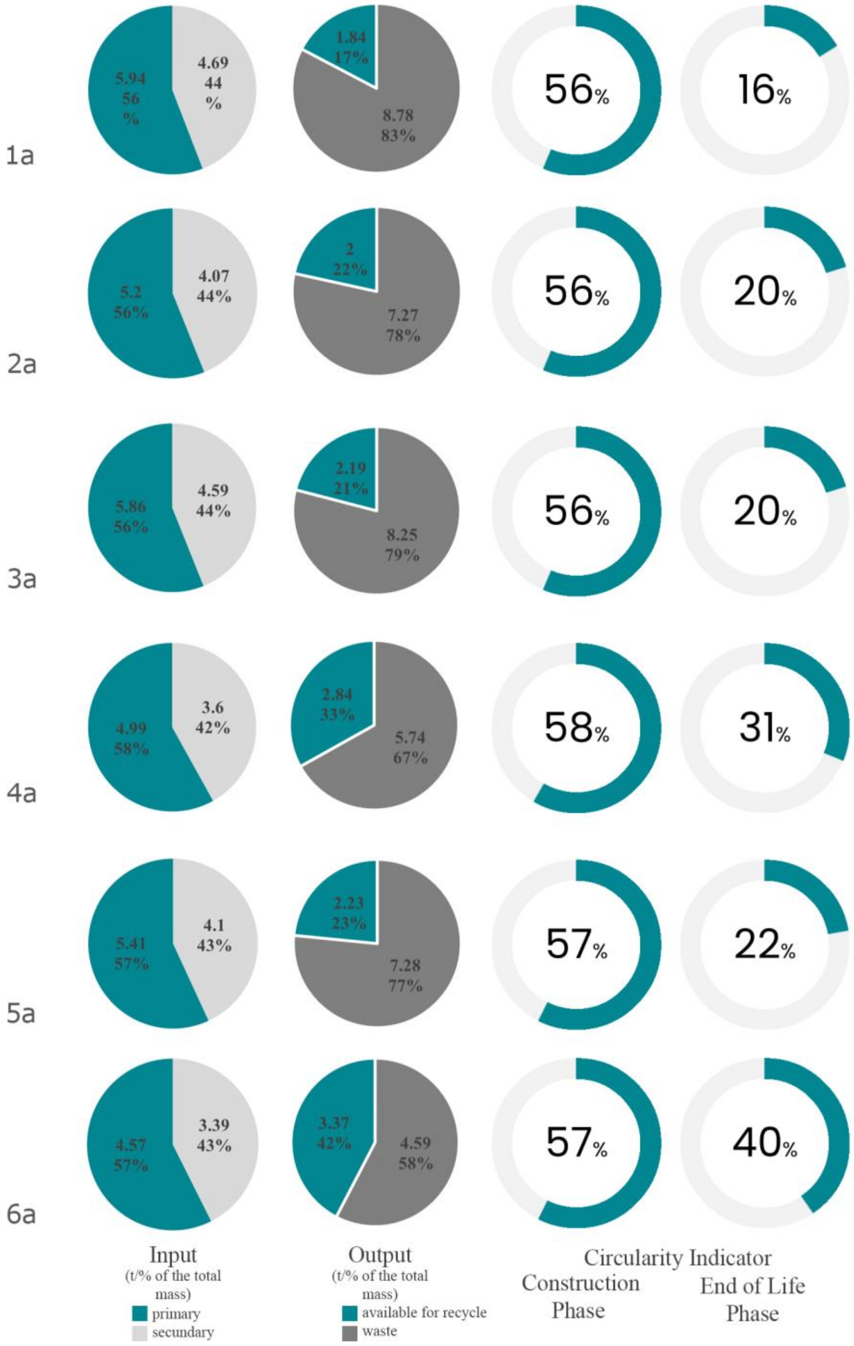

Fig. 8 Circularity indicator for the Construction and End of Life Phase for façade segments of improved models 1a-6a

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.

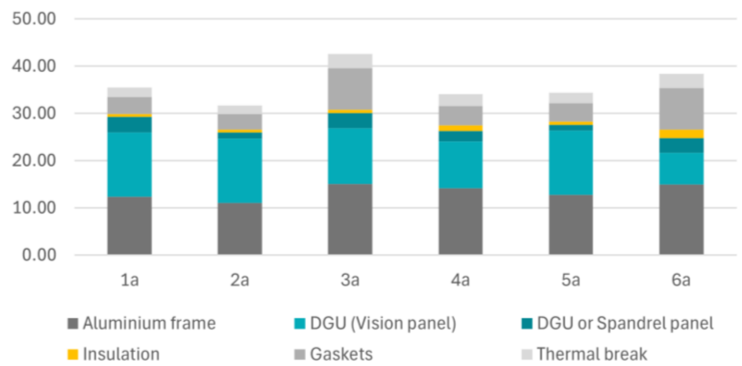

Fig. 9 Overview of the contribution of individual components to the total CO_2 emission of façade segments of improved models 1a-6a

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.

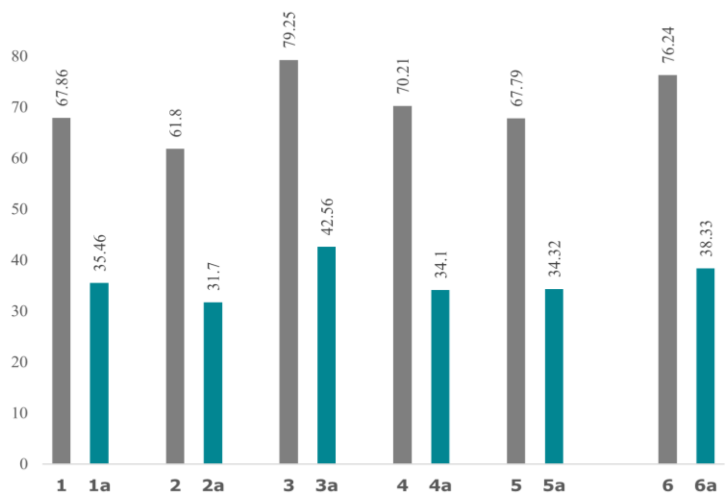

Fig. 10 Comparison of total CO_2 emission of base models 1-6 with improved models 1a-6a

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