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The impact of green roofs' composition on its overall life cycle

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Abstract

Green roof systems have been developed to improve the environmental, economic, and social aspects of sustainability. Selecting the appropriate version of the green roof composition plays an important role in the life cycle assessment of a green roof. In this study, 10 compositions of an intensive green roof for moderate zone and 4 green roof compositions for different climatic conditions were designed and comprehensively assessed in terms of their environmental and economic impacts within the "Cradle-to-Cradle" system boundary. The assessment was carried out over a 50-year period for a moderate climate zone. The results showed that asphalt strips and concrete slab produced the highest total emissions. It was found that most greenhouse gases emissions were released in the operational energy consumption phase and in the production phase. The energy consumption phase (48.78%) for automatic irrigation and maintenance caused the highest Global Warming Potential (GWP) value (758.39 kg CO_{2e}) in the worst variant, which also caused the highest life cycle cost (878.47€). On the contrary, in the best variant, planting more vegetation and lower maintenance and irrigation requirements led to a reduction in GWP (445.0 kg CO_{2e}), but in terms of cost (506.6€) this composition didn´t represent the best variant. The Global Warming Potential Biogenic (GWP-bio) compared to the Global Warming Potential Total (GWP-total) represents a proportion ranging from 0.8% to 78% depending on the proposed vegetation. Overall higher biogenic carbon values (up to 1525 kg CO_{2e}) were observed for the proposed tall vegetation of Magnolia, Red Mulberry, Hawthorne, Cherry, and Crab-apple Tree. Based on the results of the multicriteria analysis, which included core environmental & economic parameters, biogenic carbon emission levels, the outcome of this paper proposed optimal green roof composition. Optimal intensive green roof composition was subjected to a sensitivity analysis to determine the impact of changing climatic conditions on CO_2 emissions and life cycle costs. The results of the sensitivity analysis show that the optimal variant of the green roof can be implemented in the cold and subtropical zone with regard to CO_2 emissions, but not with regard to life cycle costs.

Keywords: Green roof, Life cycle assessment, Life cycle cost, Biogenic carbon

Abbreviations

ADP-E	Abiotic Depletion Potential of Elements
ADP-FF	Abiotic Depletion Potential of Fossil Fuels
AP	Acidification Potential
CDA	Concordance Discordance Analysis
CE	Circular Economy
CML	Centre of Environmental Science
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide equivalent
EP	Eutrophication Potential
EP-AF	Eutrophication Potential of Aquatic Freshwater
EP-AM	Eutrophication Potential of Aquamarine
EPS	Expanded Polystyrene
EP-T	Eutrophication Potential Terrestrial
EoL	End of Life
EPD	Environmental Product Declarations
FU	Functional unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
$GWP\text{-}_{bio}$	Global Warming Potential Biogenic
$GWP\text{-}_{fossil}$	Global Warming Potential Fossil
$GWP\text{-}_{LULUC}$	Global Warming Potential Land Use and Land Use Change
$GWP\text{-}_{total}$	Global Warming Potential Total
IPA	Importance-Performance Analysis
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Cost
MCA	Multicriterial Analysis
OCL	OneClickLCA
ODP	Ozone Depletion Potential
PE	Polyethylene
PEF	Environmental Footprint of the Product
PIR	Polyisocyanurate foam
POCP	Photochemical Ozone Creation Potential
PUR	Polyurethane foam
R	Thermal resistance
R_N	Thermal resistance standard
S1-S10	Structure of the roof 1-10
SBS	Styren-Butadien-Styren
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
U	Heat transfer coefficient
U_N	Heat transfer coefficient standard
UNEP	UN Environment Programme
US EPA	United States Environmental Protection Agency
WD	Water Deprivation
WSA	Weighted Sum Model
XPS	Extruded Polystyrene

1. Introduction

Buildings are one of the major contributors to climate change owing to greenhouse gas emissions released during their life cycle (Pique et al., 2023). Worldwide, the construction sector is reported to be responsible for approximately 40% of total greenhouse gas emissions and more than one-third of total energy consumption (UNEP, 2019). Reduction of emissions and subsequent climate neutrality in the field of construction is promised to be delivered by incorporating elements of green infrastructure (Farrell et al., 2022), as these serve as key counter-measures in fight against climate change (Chatzimentor et al., 2020; Wang et al., 2020). A green roof is a one such climate-positive green infrastructure element due to its ability to mitigate the negative impacts of urban construction, where natural green spaces decrease and impermeable surfaces increase (Sutton, 2015; Shafique et al., 2020). The positive impact of a roof covered with vegetation can be realized by its contribution to the regulation of rainwater runoff, mitigating the effect of urban heat islands, promoting biodiversity, improving a building's energy efficiency, air quality and city aesthetics (Mihalakakou et al., 2023; Tan et al., 2023; Liu et al., 2021; Marando et al., 2022).

In general, green roofs are categorized into 3 main groups: extensive, semi-intensive and intensive (Fiorentin et al., 2024; Susca, 2019; Shafique et al., 2018). Extensive green roofs require only minimal maintenance interventions. They are characterized by a thinner layer of growing substrate (8–15 cm) and are based on planting resistant greenery that tolerate extreme conditions well. On the other hand, intensive green roofs are characterized by a thicker layer of growing substrate (> 25 cm), which enables incorporation of more diverse types of vegetation from lawns to shrubs and various types of small trees. Intensive green roofs are designed in such a way that, in addition to passage, they also provide living space for inhabitants, thus creating a specific type of open green space. However, this type of green roof is more demanding in terms of building statics (effect of thickness and water absorption of the substrate on the load of the structure), construction, and subsequent maintenance. Semi-intensive roofs (15–25 cm) form the transition between extensive and intensive roofs. Extensive green roofs are considered not only environmental, but also economically more sustainable than intensive green roofs, due to their lower installation and maintenance costs (Koroxenidis et al., 2021; Teotónio et al., 2021).

Despite many advantages, green roofs are more demanding in terms of the choice of materials used and the proposed technology. Compared to conventional roofs, their installation and maintenance are more complex and more expensive (Giama et al., 2021; Manso et al., 2021). It follows that the implementation of green roofs can also lead to several environmental and economic burdens (Shafique et al., 2018). Therefore, it is important to assess green roofs from both an environmental and an economic point of view at the design stage to look for a variant of the optimal variant composition that satisfies both impacts (Vijayaraghavan, 2016; Chenani et al., 2015).

The impact assessment of various products and systems on the environment is performed during their entire life cycle, from the extraction of raw materials to the disposal of waste, using the Life Cycle Assessment (LCA) method. In construction, LCA can be used to assess the environmental impacts of building materials, products, and structures, as well as the environmental properties of entire buildings. Assessment of the costs associated with the life cycle of buildings is included in the Life Cycle Costing (LCC) methodology. By deploying LCA and LCC to assess the environmental impacts and costs of different green roof alternatives, the most environmentally and economically sustainable option can be identified (Coma, 2018, Chenani et al., 2015; Rasul et al., 2020).

The most recent review studies focusing on the life cycle assessment of green roofs point to a lack of information regarding their comprehensive environmental and economic assessment. This assessment should cover all phases of the life cycle from Cradle-to-Cradle, considering the transport and EoL (End of Life) phases, including information after the EoL (potential of renovation, recycling, or reuse of materials) (Balasbaneh et al., 2023; Fiorentin et al., 2024; Shafique et al., 2020). Life cycle assessment is recommended to be carried out in the long term in the relation to the estimated lifespan of the green roof.

Case studies conducted over the last 5 years have examined the life cycle of green roofs mostly within the boundaries of Cradle-to-User (Trovato et al., 2020; Trovato er al., 2022), Cradle-to-Gate (Nadeeshani et al., 2021; Giama et al., 2021) or Cradle-to-Grave (Ipsen et al., 2019; Brachet et al., 2019; Pushkar, 2019; Yao et al., 2020; Koura et al., 2020; Wang et al., 2020; Koroxenidis et al., 2021; Tams et al., 2022; Botejara-Antúnez et al., 2022; Pique et al., 2023) systems. The Cradle-to-Cradle approach goes beyond the Cradle-to-Grave system boundary and is more in line with the circular economy model. Compared to Cradle-to-Grave, Cradle-to-Cradle presents a more comprehensive picture enhanced by benefits and burdens addressing the EoL and disposal phases of a products or systems. It is essentially an eco-efficiency approach designed to increase positive environmental and economic impacts. Most of the authors of these studies considered a lifespan of 40-50 years for green roofs (due to the longer lifespan of the roof membrane of green roofs) and a functional unit of $1m^2$. Most studies compared green roofs with conventional roofs (Brachet et al., 2019; Koura et al., 2020; Nadeeshani et al., 2021; Koroxenidis et al., 2021; Tams et al., 2022; Pique et al., 2023), and very few studies considered comparing the properties of different types of green roofs against each other (Koroxenidis et al., 2021). Only a limited number of studies have addressed the LCA of semi-intensive and intensive green roofs (Wang et al., 2020; Nadeeshani et al., 2021; Botejara-Antúnez et al., 2022). In this context, the need for a detailed assessment of the individual layers forming the composition of the green roof was highlighted to achieve an optimal design of green roofs for future applications (Shafique et al., 2020; Vijayaraghavan, 2016). Especially, in the case of green roofs, the life cycle assessment is expected to also consider the rate of carbon sequestration by the vegetation planted on these roofs (Pique et al., 2023; Tan et al., 2023). In current studies, carbon sequestration has been determined by calculating the m^2 of the green roof over its entire lifespan (Trovato et al., 2020; Trovato et al., 2022) or by estimating the annual carbon sequestration rate based on literature values over the 40-year lifespan of the green roof (Tams et al., 2022). As these studies focus on extensive green roofs, they do not consider the impact of a wider range of specific types of greenery, such as tall greenery, on carbon sequestration throughout the life cycle of a green roof. Therefore, it is necessary to investigate the effect of different types of greenery, whether tall or low, on the carbon footprint of a green roof structure. Finally, it is desirable to expand the research to a larger number of geographical areas to obtain a more detailed overview of the sustainability of green roofs (Susca, 2019; Vijayaraghavan, 2016). Hence the importance of investigating the environmental and economic significance of intensive green roofs for their possible implementation in urban areas.

Intending to fill the missing gaps in previous research, this study aims to design and recommend the appropriate composition of intensive green roofs based on environmental and economic impacts during the whole life cycle. In addition, this study focused on the intensive type of green roof due to its ability to create a living space for active use. Ten compositions of intensive green roofs were designed and assessed to meet the basic thermal-physical requirements, mainly the thermal conductivity coefficient (U-value). Subsequently, these compositions were analysed for environmental and economic impacts using OneClickLCA software. To determine the optimal green roof composition, these were subjected to a multicriteria analysis taking into account results from life cycle assessment analysis, life cycle cost analysis and biogenic carbon. The data obtained can provide useful information to interested parties in the design and implementation of green roofs. Furthermore, the extent of the impact of changing climate zones on CO_2 emissions and life cycle costs has been investigated.

2. Methods and materials

The life cycle assessment was carried out using the Life Cycle Assessment (LCA) method. The LCA method was used to assess the environmental impacts of a product, process or service over its entire life cycle. It contained a systematic collection, analysis and evaluation of inputs, outputs and potential environmental impacts associated with economic activities. It is important to note that LCA was a complex method that required detailed data collection and knowledge of the environmental impacts of different components and processes. The LCC (Life Cycle Cost) method was used to assess life cycle costs. The life cycle costing method was a financial analysis technique used to assess the total cost of owning, operating and maintaining a product or asset over its entire life cycle. This method considered all costs associated with a product, including the cost of acquisition, installation, operation, maintenance and disposal. Life cycle analysis of intensive green roofs was carried out based on standards in force. According to these standards, the analysis was divided into 1) goal and scope, 2) life cycle inventory, 3) life cycle impact assessment, and 4) interpretation. Based on this, a multi-criteria analysis was performed to compare the compositions and provide recommendations based on sustainability criteria.

2.1. Goal and Scope

The study aimed to assess designed intensive green roof compositions over the entire life cycle and demonstrate the benefits of the conventional roof from an environmental and economical point of view. Ten variants of green roof compositions S1-S10 (Structure of the roof 1-10) adapted to the climatic conditions of Slovakia were proposed for investigation. The functional unit (FU) was set to 1 m^2 and the estimated lifespan to 50 years (Supplementary material A).

Analysis of the life cycle of investigated green roofs was performed within the system boundary "Cradle-to-Cradle". The system boundaries of the life cycle according to the standardized phase designations A1 to D were shown in Figures 1 and 2.

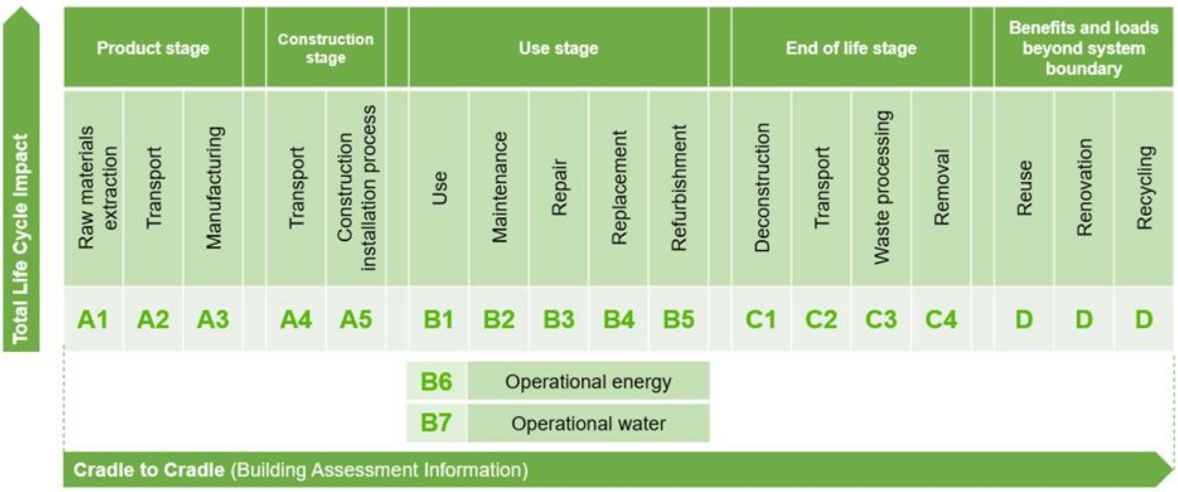

Figure 1 System boundaries in LCA

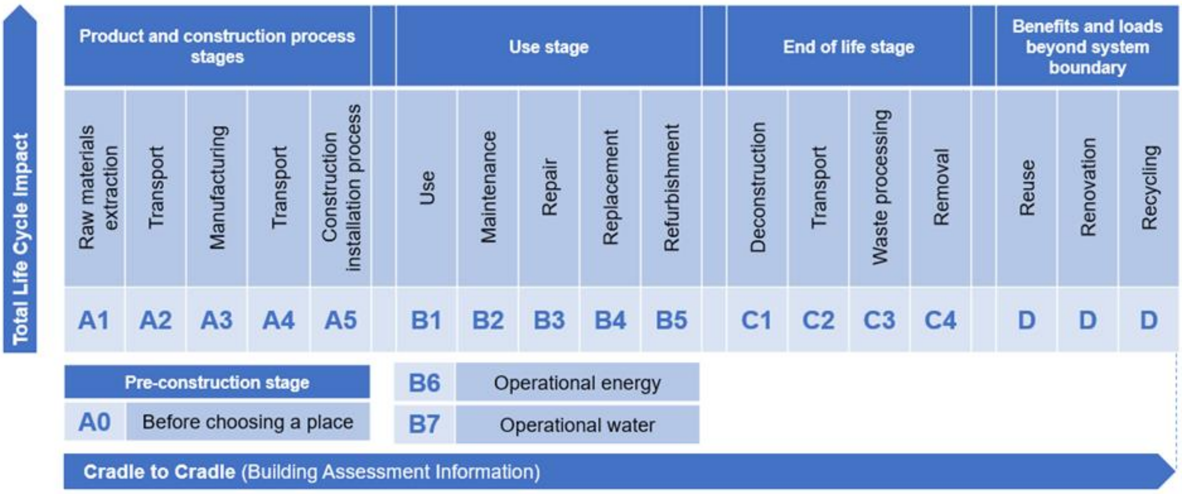

Figure 2 System boundaries in LCC

2.1.1. Software

OneClickLCA (OCL) software (version: 0.29.1, database version: 7.6) software was used for the quantification of environmental and economic indicators that comply with the standards ISO EN 14040/A1, EN 14044/A2, EN 15804+A2/AC and EN 15978. Economic assessment was completed following ISO 15686-5, EN 16627. The analysis used various databases and data sources offered by the software, such as Ecoinvent 3.8, OneClickLCA, IBU, Ökobaudat and EPD. The database for each material was provided in Supplementary material A. OCL software works according to the European approach to Sustainability Assessment Level(s), throughout the entire life cycle of a building. Level(s) is compliant with EN 15978 and the European Union taxonomy. Provides a common language for assessing building sustainability performance reports. It is a simple input for the application of principles of circular economy. It uses core sustainability indicators to measure the impacts of carbon, materials, water, health, comfort and climate change throughout the life cycle of a building. It is a flexible solution to identify sustainability hotspots (European Commission, 2021; Life for LCA LCC Level(s), 2019). Level(s) works with several tools that allow the use of generic EPDs (Environmental Product Declarations) and Type III EPDs. The Level(s) Life Cycle Assessment Tool (+A2) was used in the study - PEF 3.0 data (Product Environmental Footprint) (EN 15804+A2). The European Commission developed the PEF methodology as a tool to support various European Commissions in the area of product sustainability. The PEF methodology refers to the following standards: ISO 14040, ISO 14025, ISO 14067 and ISO 14020. The general purpose of the PEF is to promote European policy as a potential methodology for regulations. The general purpose of the EPD standard is to support communication and regulations. EPD data are also used for the purpose of building life cycle assessment at project level according to related EN 15978 and other standards. Both the PEF and EPD methodologies can be considered robust for the task at hand. In the EPD methodology, programme operators are responsible for quality assurance of verifiers and published EPDs. PEF approaches quality with scoring requirements (OneClickLCA, 2022; S. Masson, 2024). The Life Cycle Cost (ISO 15686-5 and EN 16627) - CML (Centre of Environmental Science) method was used for the cost assessment. OneClickLCA supports all 24 impact categories listed in EN 15804 according to the CML methodology. For all instruments targeting European markets, the impact assessment methodology is CML-IA 2012, which is the methodology required by the European standards EN 15978 and EN 15804 (OneClickLCA, 2023).

2.1.2. Statistical analysis

2.1.2.1. Multicriteria analysis

Multicriteria evaluation methods allow us to evaluate compare different alternatives on the basis of several criteria, defined by indicators. This analysis has allowed different aspects and preferences to be taken into account in the decision-making process and has helped to identify the best possible solution with respect to the given criteria. The contribution of the MCA (multicriteria analysis) is that multiple methods have been used within the multicriteria analysis to validate the result. These methods are used to evaluate and compare alternatives in different ways based on the criteria and preferences identified. Each of these methods has its own advantages and limitations and may be suitable for different types of decision-making situations. Laurin et al. (2016) explain that MCA can enrich LCA results by providing studied methods for evaluating trade-offs, mainly because it allows for a broader view of different aspects (Manzardo et al., 2014). Accordingly, Kucukvar et al. (2014) explain that this integration can provide guidance to decision makers, which can significantly contribute to the development of sustainable strategies. Conceptually, MCA is introduced in the LCA framework and standards as a 'weighting' step. This kind of combined application is essentially based on the use of the MCA concept to aid in the interpretation of the LCA (Agarski et al., 2016). Therefore, in general, the combination of MCA and LCA can occur in two ways: LCA can be used to add an environmental indicator to the MCA process and the MCA can be used to interpret the LCA results. The reasons for combining these tools are many, but according to Hermann et al. (2007), the main one lies in their complementary characteristics. MCA was performed using the MCA7 tool (Korvin, 2010). The analysis included all LCA and LCC categories.

2.1.2.1.1. Methods applied in multicriteria analysis

The statistical methods available in the MCA7 tool that were assessed included CDA (Concordance Discordance Analysis) (Hradílek et. Al., 2003), IPA (Ideal Points Analysis) (Doubravova et. al. 2009), WSA (Weighted Sum Approach) (Chalupkova et al., 2010), and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) (Papathanasiou et al., 2018). The CDA method was based on pairwise comparison of choice alternatives. It analysed the extent to which the choice of alternatives and factor weights confirmed or refused the relationship between the alternatives. The IPA method relied on a comparison between a set of ideal solutions and a set of efficient solutions. Although ideal solutions were almost non-existent, they served as an important reference point. The best compromise solution was determined as the one that was closest to the ideal solution. The WSA method was based on weighted summation and calculated the values of the linear utility function. The TOPSIS method aimed to minimize the distance from the ideal alternative. The CDA method is more comprehensive and provides scope for rigorous comparison and consideration of preferences. The WSA method is simpler but does not take into account interactions between criteria. The IPA method is suitable for optimisation where the best solution is determined. The TOPSIS method provides an objective comparison of alternatives. For the purpose of LCA evaluation in this study, TOPSIS and IPA methods are preferred, the other methods are only confirmatory.

2.1.2.1.2. Evaluation criteria and weights

This method ranked all the variants and allows the selection of the best option based on how close it was to the ideal variant. Using the MCA7 tool, a multi-criteria analysis was performed to select the optimal vegetation roof composition. In the MCA analysis, 14 indicators (GWP-total, GWP-fossil, GWP-biogenic, GWP-LULUC (Land Use and Land Use Change), ODP (Ozone Depletion Potential), AP (Acidification Potential), EP-AF (Eutrophication potential of aquatic freshwater), EP-AM (Eutrophication Potential Aquatic Marine), EP-T (Eutrophication Potential Terrestrial), POCP (Formation Potential of Tropospheric Ozone), ADP-E (Abiotic Depletion Potential for Non-Fossil

Resources), ADP-FF (Abiotic Depletion Potential for Fossil Resources), WU (Water Deprived) and LCC) were considered with assigned importance weight. Indicators with global environmental impact (GWP, ODP, ADP-E) were assigned a significance weight of 35%. Indicators with regional environmental impact (AP, EP, POCP) were assigned a significance weight of 20% and indicators with local impact (ADP-FF, WD) were assigned a significance weight of 5%. A significance weight of 40% was assigned to the economic indicator (LCC nominal) and the sum of the weights equals 1. The results were presented in Supplementary material C.

2.1.2.2. Sensitivity analysis

Sensitivity analysis is a statistical method used in planning and prediction. It determines how the outcome of a model will be affected if its input variables are changed (Zhou et al., 2023). Within the framework of this study, a sensitivity analysis in the form of a scenario analysis was performed. (Björklund, A. E., 2002). Three scenarios were created by modifying the baseline intensive green roof model (S8). The aim of this analysis was to identify differences in environmental and economic impacts when applying the most optimal variant of the intensive green roof (baseline model) in different climate zones and thus to investigate the global applicability of the S8 assembly. In the case of environmental impacts, the key input variable is assumed to be the thickness of the thermal insulation, which is most likely to affect the overall outcome. In addition to the thickness of the thermal insulation, the price of the materials played a key role in the assessment of the economic impacts. The scenarios included alternative models for adaptation to cold and two subtropical climate zones. The selected countries are representative of different climatic zones with the occurrence of green roofs and the availability of information regarding the thermal performance requirements of the envelope, including the cost of the materials used. Greenery proposed in the baseline assembly (S8) represents native plant species suitable for their planting in different climatic zones. In this context, the aim was to design an assembly that would be usable in different climatic zones with only minimal intervention in its layer structure. The baseline model considered a structure set in a moderate climate zone (Slovakia). The thermal insulation thickness was based on the thermal requirements (resistance and heat transfer coefficient of the roof structure) of the studied area: the cold climate zone (Finland), the subtropical zone 1 (Italy) and the subtropical zone 2 (Cyprus) (Supplementary material D).

2.2. Life cycle inventory analysis

Life cycle inventory (LCI) analysis was used to calculate greenhouse gas emissions during the entire life cycle of the roof. The roof compositions were designed to be trafficable and met the thermal technical requirements for roofs with heat transfer coefficient (U-value) and thermal resistance (R-value) according to the STN (Slovak technical norms) standard 73 0540-2+Z1+Z2.

2.2.1. Composition of intensive green roof

The green roof design, depicted on Figure 3, was based around the reinforced concrete slab used as the load-bearing base layer for all ten variants of the green roof. The intention of the design considered load applied by the layers installed layers, especially the wet substrates, which could significantly affect the structural integrity of the roof. In selected variants of the roofs, polyethylene or polypropylene foil or asphalt-based coating was applied. The next layer was thermal insulation, featuring a high compressive strength sufficient to withstand the weight of the substrate. However, from a thermal-technical point of view, it was also necessary to take into account the coefficient of thermal conductivity λ and the factor of diffusion resistance μ. Several types of thermal insulation were used in this study, such as expanded polystyrene EPS, extruded polystyrene XPS, polyurethane foam PUR or insulation based on polyisocyanurate PIR. The next layer consisted of waterproofing, which was separated from thermal insulation with a separation film (geotextile). Geotextile was used if the waterproofing layer was based on asphalt strips. Softened PVC film or asphalt-based waterproofing was used in all roof variants. Waterproofing in several variants merged directly with the root membrane; in others a PVC-based foil was added. A drainage layer was placed above the waterproofing layer, which drained excess water from the roof and at the same time protected the root system of plants from rotting. As a drainage layer, a drainage foil was used, on top of which a filter layer (geotextile) was applied. This layer separated the substrate from the drainage layer. The upper layer consisted of a substrate with vegetation. The thickness of the substrate depended on the selected vegetation. In the case of an intensive roof, a thicker layer was installed. The thickness of the substrate ranged from 250 to 450 mm. All building materials and their quantities can be found in the attachment (Supplementary material A). In order to take of account, the impact of transport on the environment, the analysis also considered the transport distance between the production plant and the application site. The location of the manufacturing plant for each material and the shipping distance are listed in the appendix (Supplementary material B). The unit prices for the material were obtained from the price database of the construction software Cenekon Cenkros 4 and were also listed in the appendix (Supplementary material B). All compositions were converted to FU 1m^2. The OCL software worked according to the CML and PEF methodology and the European approach to Level(s) assessment. Ecoinvent 8.3, OneClickLCA, IBU, Ökobaudat and EPD (Environmental Product Declarations) and other databases and data sources were used in the analysis, as well as data from EPDs. Materials that were not included in the OCL software database were replaced by materials from other manufacturers or were considered with materials that have calculated average values of environmental impact indicators. These materials are waterproofing membrane and substrate, which were selected similar to those identified in the design. The selected materials are listed in Supplementary Material A. The environmental and economic life cycle assessment of the roofs was carried out using the OCL software, which was in accordance with the LCA and LCC methods. The compositions were evaluated within the limits of the "Cradle to Cradle" system for a lifespan of 50 years. Considering the need to irrigate vegetation (especially lower greenery and lawns) at regular intervals, operational energy and water were included in the LCA and LCC analysis. Electricity consumption for S1, S6 and S7 is 27 kWh/year and water consumption for irrigation is 0.61 m^3/year. For compositions with taller green S2, S3, S4, S5, S8, S9 and S10, the energy and water consumption was calculated as 13.5 kWh/year and 0.30 m^3/year, respectively.

Figure 3 Basic composition of an intensive green roof

2.2.2. Vegetation

The composition used for the lower vegetation consisted of: Melica ciliata (S1), Anthemis tinctoria (S6), Lawn carpet (S7) and taller vegetation, more specifically Dogwood trees (S2), Magnolia (S3), Ginkgo biloba (S4), Red Mulberry (S5), Hawthorne (S8), Cherry (S9) and Crab-apple tree (S10). Carbon sequestration for low vegetation such as ornamental grasses, perennials and lawn carpets were not included in the OCL database. Therefore, carbon sequestration values based on research conducted at the Ohio State University in the USA were used (Zirkle et al., 2011). The basic composition of a green roof, using all layers, was presented in Figure 3. Carbon withdrawals for vegetation and landscaping during the project´s lifespan were accounted for in the biogenic carbon storage category only. This was accounted for according to the method developed by the US EPA (United States Environmental Protection Agency) (Method for Calculating Carbon Sequestration by Trees in Urban and Suburban Settings).

2.3. Life cycle impact assessment

In the Life Cycle Impact Assessment (LCIA) step, all collected inventory data of the compositions were evaluated. The LCA approach enabled the assessment of many categories of environmental impacts. Table 1 shows the impacts of the categories assessed. Some impacts were classified as global because their environmental mechanism was the same regardless of where the emissions occur.

2.3.1. Evaluation indicators

Global indicators include GWP, ODP and ADP-E. Others, such as AP or EP or POCP, were regional in nature and affected a smaller area directly downstream of where the emissions enter the environment. Impacts affecting a small area were designed to be local, this includes for example ADP-FF and WD (Hauschild et al., 2018). For global indicators (>100 km^2), the nature of the area in which emissions were released was found to have no effect on the type and scale of the associated potential impact. Conversely, for regional impacts (>10<100 km^2), the nature of the area was found to produce a larger impact. Regional impacts affect a (sub)continent or just a smaller area around the point of emission. The differential impact of e.g. eutrophication would also be impacted by geographical location featuring e.g.: marine coastline, another body of water or just land. Impacts affecting a small area are referred to as local impacts (0-10 km^2) (impacts on water or direct impacts of land use on biodiversity). Other factors that could potentially be assessed included human health impacts, toxicity in the landscape, freshwater and ocean, air and water pollution, land degradation, physical disturbances such as soil erosion, and changes in landscape quality (Rosenbaum et al., 2018).

Table 1 Parameters describing core environmental impacts

Impacts categories	Abbreviation	Unit
Global Warming Potential total	GWP-total	kg CO_{2e}
Global Warming Potential fossil	GWP-fossil	kg CO_{2e}
Global Warming Potential biogenic	GWP-bio	kg $CO_{2e\ bio}$
Global Warming Potential, LULUC (Land Use and Land Use Change)	GWP-LULUC	kg CO_{2e}
Depletion potential of the stratospheric ozone layer	ODP	kg $CFC11_{e}$
Acidification potential	AP	mol H+ eq.
Eutrophication potential of aquatic freshwater	EP-AF	kg Pe

Eutrophication potential of aquatic marine	EP-AM	kg N $_{eq.}$
Eutrophication potential of terrestrial	EP-T	mol N $_{eq.}$
Formation potential of tropospheric ozone	POCP	kg NMVOC $_{eq.}$
Abiotic depletion potential for non-fossil resources	ADP-E	kg Sb_e
Abiotic depletion potential for fossil resources	ADP-FF	MJ
Water use m^3 deprived	WD	m^3

2.3.2. Biogenic carbon

A separate impact category was biogenic GWP ($CO_{2e\ bio}$), which shown a positive impact on the environment. Carbon sequestration in growing vegetation meant that plants removed carbon dioxide from the air during photosynthesis, which they then convert to oxygen (Lal, 2008, Ariluoma et al., 2021). Carbon produced by plants can be stored in their root system, branches, leaves, and flowers. Around 6 kg of CO_2 can be absorbed by a young tree during their first years of growth. Trees in the most productive phase of carbon storage, which occurs around ten years after planting, can potentially store up to 20 to 60 kg CO_2/year. The main governing factor of this carbon storage capacity is the tree species itself (Afzal et al., 2013). Vegetation has been divided into low (lawn carpet, ornamental grass up to 70 cm) and tall (trees reach an average height of 3.0-3.5 m). Tall trees with a relatively long-life span enable the greatest positive impact on the environment and carbon dioxide production. In addition to trees, low-lying vegetation such as grass, which stores biogenic carbon in its roots, can also sequester harmful carbon dioxide. In this case the carbon storage ranges between 46 to 127.1 g C/m^2/year (Zirkle et al., 2011). In addition to the LCA, an LCC analysis was also carried out. The LCC analysis was based on long-term costs and savings, which are interlinked. Using LCC it was possible to quantify life cycle costs without or including inflation. In the case of a non-inflationary calculation, the costs were assumed to be the same over the entire calculation period. The calculation including inflation also considers possible price increases for construction materials and works. The LCC helps to find the most sustainable and cost-effective solution. LCC analysis was the most accurate way to increase the savings of the analysed building or building materials by comparing different alternatives (OneClickLCA). The values used in the study were nominal and include estimated inflation.

3. Results and Discussion

3.1. LCA results

3.1.1. LCA results for global indicators

The life cycle assessment examined global, regional, and local impact categories. Figure 4 presents emissions of global indicators for each life cycle phase.

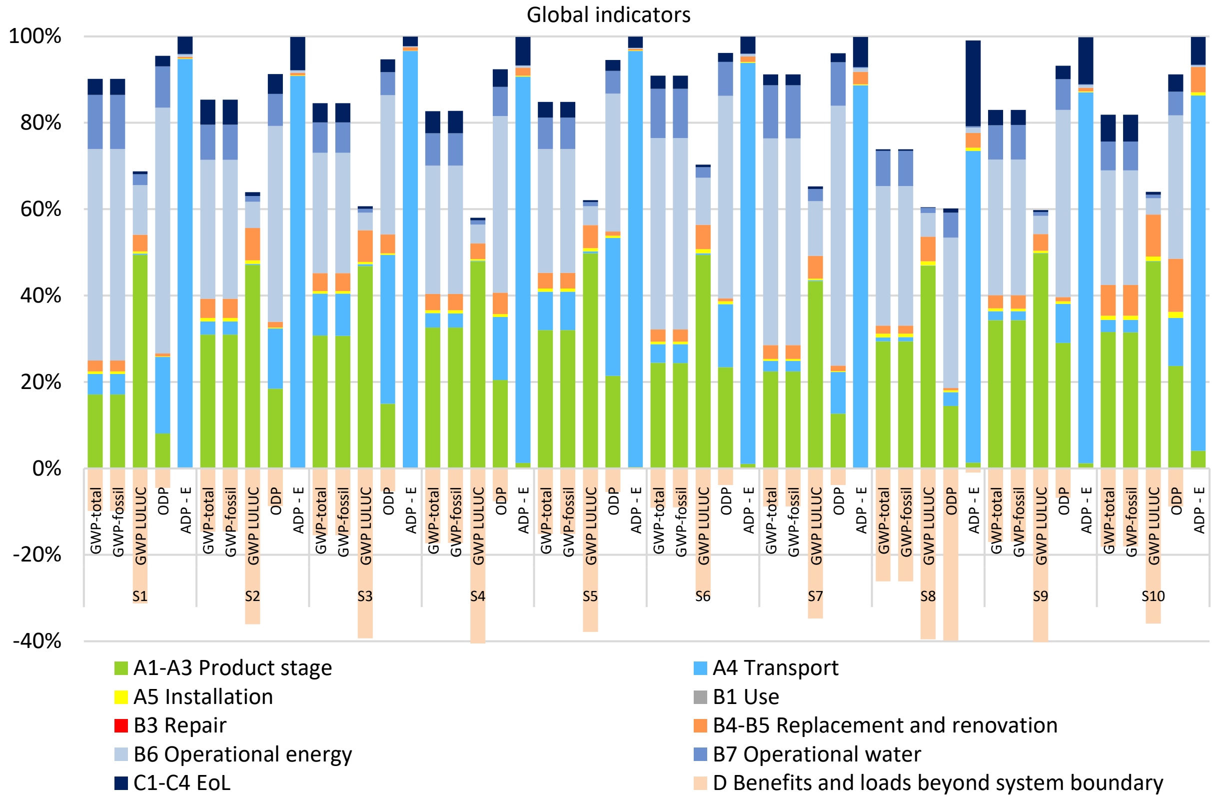

Figure 4 Emissions of global indicators for each life cycle phase in percentages

Composition S6 was found to have the largest negative impact, followed by composition S7 in terms of GWP-total and GWP-fossil. For almost all assessed compositions (S1–S10), the increase in total GHG emissions (measured in equivalent CO_2) was due to the operational energy (B6) required for automatic irrigation of green areas. It can be concluded that vegetation requiring more intensive irrigation in the seasonal period resulted in a higher energy intensity and a higher environmental impact. The product phase A1-A3 also contributed a major share to the GWP categories. Related to composition S6 and S7, the most contributed material to the GWP-total was reinforced concrete slab followed by insulation and vegetation substrate. These materials produce 186 kg CO_{2e} (S6) and 142 kg CO_{2e} (S7), representing 90.8% (S6) and 82% (S7) of all materials used in these compositions. XPS contributed 21.06 kg CO_{2e}/m^2 and was one of the dominant contributors, but not the largest. Contrary to the study by Vacek et al. in which XPS thermal insulation accounted for 44.6 and 36.25 kg CO_{2e}/m^2 in the two evaluated compositions of semi-intensive green roofs and was thus among the largest contributors (Vacek et al., 2017). These arguments were also supported by a study by Chenani et al., in which it was estimated that mineral wool and plastic layers have the highest environmental impact (Chenani et al., 2015). In the case of both studies, the reason was the omission of the load-bearing roof structure in the assessments (Chenani et al., 2015). This was due to the omission of the load-bearing roof structure in the assessments (Vacek et al., 2017; Chenani et al., 2015). For all GWP categories, composition S8, which did not use a SBS modified asphalt-based membrane and PIR thermal insulation, came out best. According to the results obtained, the S8 composition achieved the worst impact on the ozone layer. In all cases, the operational energy module (B6) influenced the ODP values the most. Reinforced concrete slabs contributed the most to the ODP (2.70E^{-06} kg $CFC11_e$). EPS rigid foam insulation (9.20E^{-15} kg $CFC11_e$) shown the lowest impact of all the materials. In terms of ADP-E, compositions S3 and S5, and module A4 revealed the worst environmental impacts. Volcanic lava substrate (6.3E^{-5} kg $Sb_{eq.}$) shown the greatest impact in category of ADP-E. The material with the lowest impact was the polyethylene vapor barrier membrane (7.90E^{-6} kg Sb_{eq}.). In the composition considered in the study by Vacek et al. the highest ADP-E and ODP was due to the use of engineered materials such as mineral wool or XPS. Compositions S10 and S8 manifested the lowest values due to the use of materials producing lower or no kg Sb_{eq} such as PVC-based waterproofing membrane and expanded thermal insulation. The EoL (C1-C4) presented the lowest environmental impact. Benefits and loads from incineration, landfilling and reuse within module D for the global indicators represent a range of 11-55% for all compositions.

3.1.2. LCA results for regional indicators

The results of regional indicators assessment for each life cycle phase are presented in Figure 5.

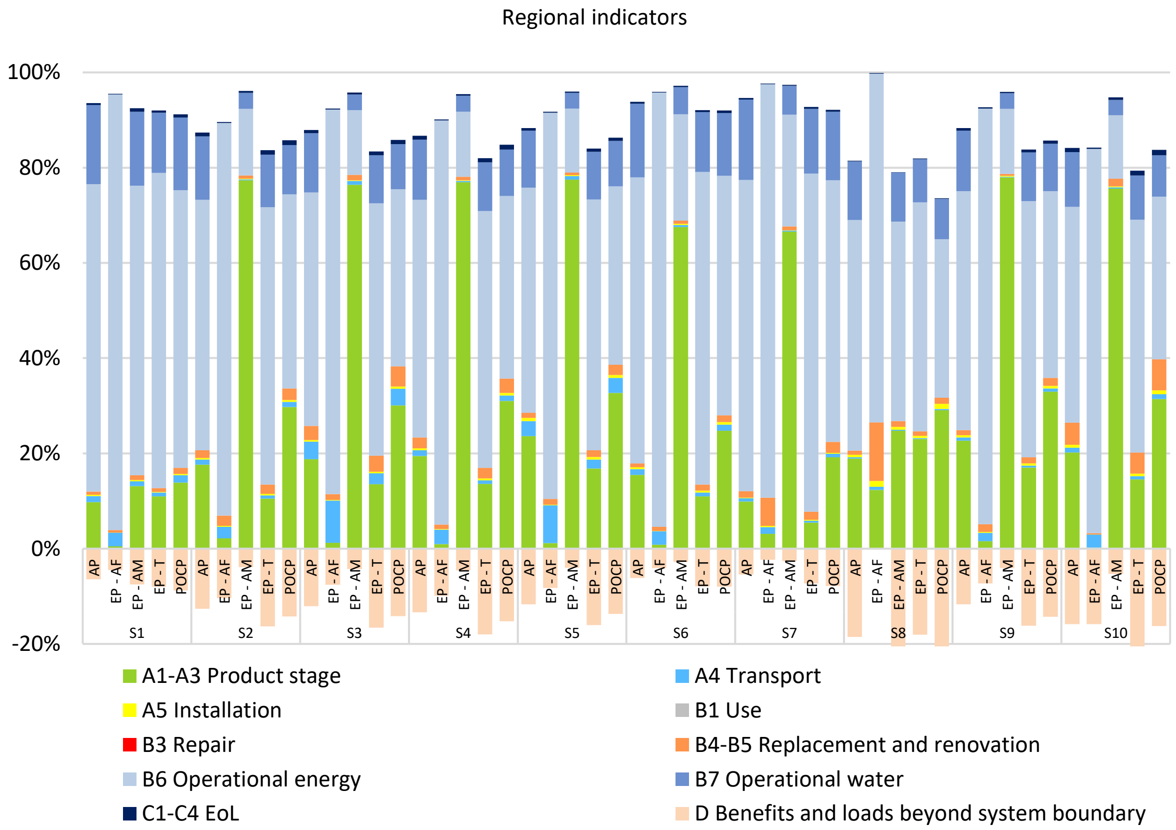

Figure 5 Emissions of regional indicators for each life cycle phase in percentages

For all regional indicators, the operational energy module (B6) was significant, except for the EP-AM indicator, where the product phase (A1-A3) was the most represented. Regarding the worst impact among all regional indicators, this was found in composition S6. The EoL (C1-C4) revealed the least impact. In the S6 composition, the three materials with the highest contribution to total AP emissions were reinforced concrete slabs, PUR/PIR foam insulation, and vegetative substrate. Together, they emitted 0.67 mol $H+_{eq}$, representing 89.33% of the total AP potential of all materials. In the EP-AM (1.18 kg N_{eq}) and POCP (0.31 kg $NMVOC_{eq}$) categories, the highest emissions were also achieved by the reinforced concrete slab. On the other hand, in the EP-AF and EP-T categories the plastic waterproofing membrane (5.5E^{-05} kg Pe) and PIR insulation (polyisocyanurate foam) (0.65 mol N_{eq}) showed the highest impacts, respectively. Regarding module D, the benefits and burdens beyond the system boundary for the regional indicators represented a percentage range of 3-30% taking into account all compositions.

3.1.3. LCA results for local indicators

The percentage representation of emissions of local indicators for each life cycle phase is shown in Figure 6.

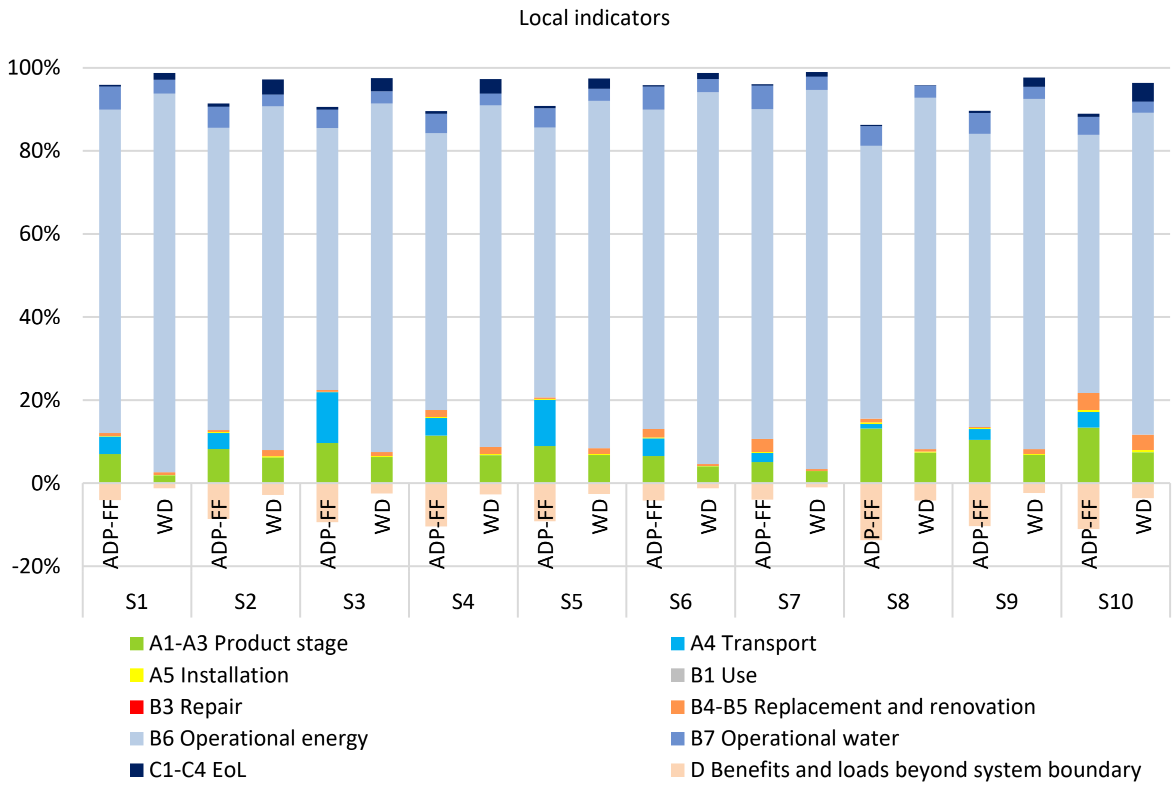

Figure 6 Emissions of local indicators for each life cycle phase in percentages

In terms of ADP-FF and WD, the S6 composition indicated the worst environmental impact. The phase that contributed the most to the local indicator emissions was operational energy B6 (more than 70%). The phase that affected the emissions the least was the EoL (C1-C4). The PIR insulation board (891.03 kg MJ) contributed the most to ADP-FF and the reinforced concrete slab (43.38 m^3) contributed the most to WD. For the regional indicators, Module D revealed a range of 1-19% for all compositions.

A study according to Wang et al. conducted in China, concluded that semi-intensive green roofs contributed to environmental impact reduction and energy savings in the use and maintenance phase and was thus the primary cause of environmental improvements (Wang et al., 2022). In a comparative study of an intensive green roof and a conventional roof, the authors Nadeeshani et al. found that the operational phase has the highest share of the carbon footprint of both types of roofs. The results further revealed that the life-cycle carbon emissions of the intensive green roof were 84.71% lower compared to the conventional concrete flat roof. It was therefore concluded that the use of green roofs was a suitable alternative to improve the green environment with significant potential to reduce carbon emissions during the life cycle of the building (Nadeeshani et al., 2021). The CO_2 emissions of the whole green roof were 699.7 kg/m^2. Compared to the worst-case variant (S6) of this study with emissions of 758.39 kg CO_2/m^2, this represented a negligible difference. Comparing with the conventional roof, the results showed that the life cycle carbon emissions of the intensive green roof were 84.9% lower. The study confirms that the operational phase contributed to increased environmental impacts.

3.1.4. Results for biogenic carbon

It is important to note that the carbon sequestration potential of green roofs depended on a variety of factors such as vegetation type, substrate depth, climate and maintenance. Various plant species accumulate carbon at different rates. Carbon sequestration depends on various factors such as height and density of vegetation. Taller and denser vegetation can sequester more carbon because it has a larger surface area for photosynthesis and biomass accumulation. Soil substrate, temperature, rainfall and the intensity of solar radiation can affect plant growth and thus their ability to sequester carbon. As plants age, carbon sequestration may increase because plants accumulate more biomass as they grow. Plants with a fast growth rate that reach a height of 10 to 40 m (ash, poplar, lime, magnolia maple, mulberry, oak) sequester 55.22 kg CO_{2e}/year. Plants that reach 10 to 75 m (pine or spruce) sequester 47.84 kg CO_{2e}/year. Biogenic carbon storage for plants with medium growth rates that reach 5 to 50 m in height (juniper, tule, spruce) is 25.34 kg CO_{2e}/year. Plants between 4 and 30 m (birch, cherry, hawthorn, elm and lower species of oak) achieve 30.51 kg CO_{2e} of biogenic carbon storage per year. Plants with slow growth rates that reach a height of 4 to 50 m (beech, ginkgo, walnut, maple) sequester 13.68 kg CO_{2e} and those from 5 to 40 m (fir, black pine, red spruce) sequester 10.76 kg CO_{2e}. Lawn carpet and Anthemis tinctoria sequester 6.35 kg CO_{2e}/year. Carbon sequestration on green roofs can also be influenced by factors such as microclimate, air quality and precipitation. However, these factors require additional research and should be taken into account in the planning and implementation of green roofs to maximise their contribution to reducing greenhouse gas emissions and improving environmental quality in urban areas (OneClickLCA; 2022).

From the comparison it was found that S8 (Red mulberry) presented the highest biogenic GWP potential, while S1 (Melica ciliata), S6 (Anthemis tinctoria) and S7 (Lawn carpet) (6.35 kg $CO_{2e\ bio}$) shown the lowest biogenic GWPs. However, when selecting a composition for a given project, it was important to consider the overall environmental impact of the green roof, including its carbon footprint and other potential environmental impacts. Average biogenic carbon storage values of tall green vegetation such as trees with slow, medium and fast growth rates were obtained from the OCL software database. Cover-crop variability over time was not accounted for. For slow growth trees, 13.68 kg, 30.51 kg and 55.22 kg of stored biocarbon per year were considered for slow, medium and fast growth trees, respectively. The tall vegetation was on the roof of S2 (Dogwood) with a value of 684 kg bio-CO_2, S3 (Magnolia large-leaved) with a value of 1525. 5 kg $CO_{2e\ bio}$, S4 (Ginkgo biloba) with a value of 684 kg $CO_{2e\ bio}$, S5 (Red Mulberry) with a value of 2761 kg $CO_{2e\ bio}$, S8 (Hawthorn) with a value of 1525.5 kg $CO_{2e\ bio}$, S9 (Bird Cherry) with a value of 1525.5 kg $CO_{2e\ bio}$ and finally S10 (Crab-apple) with a value of 1525.5 kg $CO_{2e\ bio}$. Low green vegetation such as ornamental grasses, perennials and grass carpets were not included in the software database. In this case, biogenic carbon storage values were used based on research presented in a study conducted at Ohio State University, (Zirkle et al., 2011). The research showed that low green areas store around 127 grams of biogenic carbon per FU of area per year. Low green area was proposed for S1 (Melica ciliata), S6 (Anthemis tinctoria) and S7 (Lawn carpet) roofs. Moreover, the study where authors Pique et al. evaluated four types of roofs namely conventional, extensive, semi-intensive and intensive in a subarctic climate confirms the positive impact of green roofs on the environment. It was also stated that green roofs with a lifespan of less than 45 years increased their carbon impact. For this type of climate zone, carbon sequestration plays a minor role (Pique et al., 2023). Therefore, an appropriate choice of green roof composition and its vegetation in relation to the climatic conditions was necessary. In a study by Castleton et al. they concluded that the selection of appropriate vegetation supported the reduction of the carbon footprint and energy losses of a building (Castleton et al., 2010). Carbon sequestration increased in direct proportion with proper plant selection and changed in substrate depth, substrate composition, as reported by the authors in a study of green roofs

(Rowe, 2016). This was true whether the landscape was on the roof or at ground level. Vegetation and soil characteristics were found to be key factors influencing building energy reduction and CO_2 sequestration performance (Seyedabadi et al., 2021, Seyedabadi et al., 2022). In variant S6 (Anthemis tinctoria), GWP-bio contributed 0.83%, and in variant S8, due to the application of tall green vegetation (hawthorn), GWP-bio contributed up to 78.3%. This fact that tall vegetation was able to contribute to the GWP-bio to a greater extent represents the positives of intensive green roofs. From this point of view, more attention should be paid to intensive type of roofs.

3.2. LCC results

Based on an evaluation of the life cycle costs of variants of intensive green roof compositions, presented in Figure 7, revealed the S7 possessing the highest costs. On the other hand, the lowest costs were indicated by S3. This was due to the effect of the irrigation system which impacted the operating costs and thus the total costs. Composition S7 with the highest life cycle costs presented the operating energy module (B6) with value of 612.84 €. Higher costs were observed also in the product phase (A0-A5) with value reaching 108.33 € and during water consumption phase (B7) consuming 87.3 €. Composition S7 with the lowest life cycle costs exhibited the EoL (C1-C4) in the amount of 7.44 €. It is worth noting that all cycle cost phases of the intensive green roof options were presented in Figure 8.

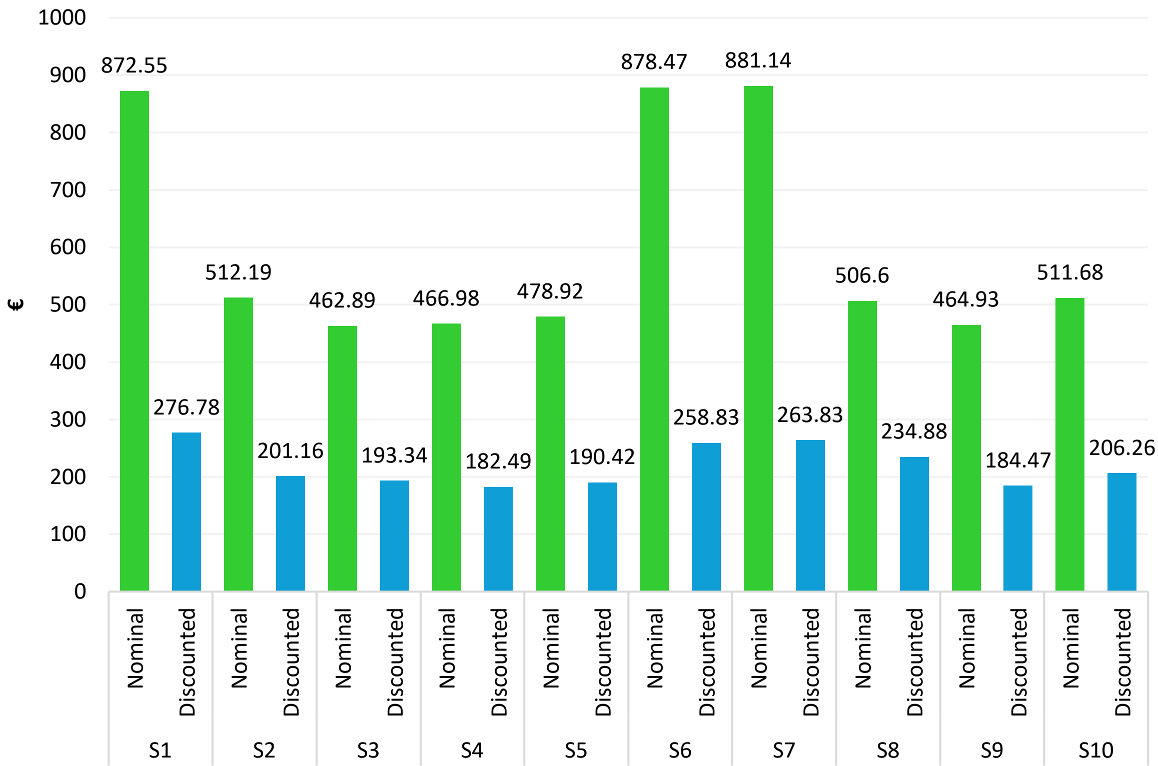

Figure 7 Nominal and discounted life cycle costs of variants of intensive green roof compositions

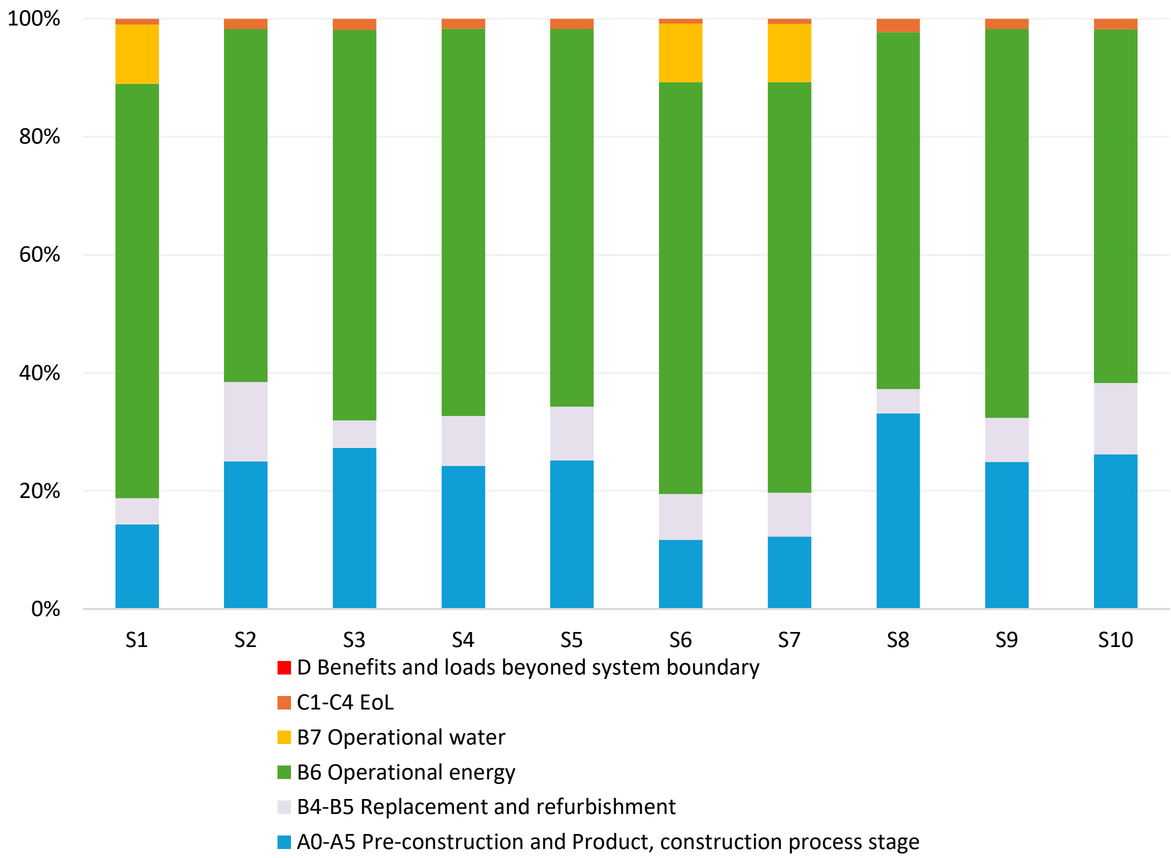

Figure 8 Costs of life cycle phases of variants of intensive green roof compositions

Kim et al. (2018) found that intensive green roofs showed a higher environmental impact and higher costs than conventional roofs due to higher replacement and maintenance requirements. They highlight the need to improve the economic and environmental sustainability of green roofs. The total cost for the intensive roof type was 171.5 €, however, not including the cost of the roof support structure. The compositions (S1-S8) proposed in this study also considered the cost of the supporting structure, which could have increased both the input and the operational costs. Kim et al. also did not use irrigation in their study, they only investigated runoff and stormwater retention.

The environmental and energy benefit of green roofs was clearly demonstrated in a study by Ziogou, however, the economic benefit could be achieved by reducing current installation costs. Peri et al. pointed out in their study the advantages of evaluating green roof costs throughout the life cycle and emphasized the EoL phase. The evaluation showed that up to 44% of the total initial costs are caused by the growth medium (Ziogou, 2023, Peri et al., 2012). At the end of the study, the authors stated that the availability of information on the phase of liquidation of building materials and the availability of foundation data would contribute to the more frequent use of green roofs and thus help to meet the sustainability criteria. The results of our study showed that the cost reductions can be achieved by planting taller vegetation that is less demanding in terms of energy consumption, water for irrigation and overall maintenance. For the proposed compositions (S1-S10), the EoL phase caused the lowest emissions. In the study by Peri et al., the initial cost of an extensive green roof was 240€/m^2. The authors point out that the growth medium accounts for up to 44% of the initial cost, which a study of intensive roofs can confirm (growth medium - 37.7%). Maintenance costs were quantified at 3 €/m^2/year, watering, fertilizing and weed pulling costs were included. Disposal costs were 11.95 €/m^2. The growth medium in the study of extensive roofs accounted for up to 85% of the total disposal costs. In the study of intensive green roofs (S1-S10), the initial cost was between 103.3 and 167.8 €/m^2. The initial costs are higher in the case of the extensive roofs study. Maintenance and operating costs were in the range of 6.5 to 15.4 €/m^2/year. However, in the case of the intensive green roofs (S1-S10), an irrigation system was used that requires both electricity and water, which will increase the costs considerably. Disposal costs ranged from €7.77 to €11.52/m^2. The growth medium accounted for only 27.4% of the total disposal cost, the reinforced concrete floor slab was also included in the calculation and accounted for 28%. In the study of extensive green roofs, the authors did not include the reinforced concrete floor slab in the calculations, and our study shows that it accounted for 38% of the initial cost and 28% of the disposal cost.

By choosing the end-of-life phase appropriately, overall GHG can be reduced. These findings support the conclusions of the authors Ziogou and Peri et al. (Ziogou, 2023, Peri et al., 2012). Other studies also support this claim (Giama et al., 2021, Yao et al., 2018). In the study by Giama et al., the authors found that upfront costs are the largest and sometimes cannot be offset by the expected gains from reduced energy and operating costs. In addition, maintenance and layer replacement issues are parameters that increase life cycle costs. The extensive green roof required maintenance costs of around 1.60 €/m^2/year, while the maintenance costs of an ordinary flat roof amounted to 1.08 €/m^2/year. For comparison with this study, the maintenance costs of intensive green roofs (S1-S10) ranged from 0.41 to 1.37 €/m^2/year. In the most optimal green roof composition S8, the maintenance costs amounted to 0.41 €/m^2 per year. The extensive green roof used meadow grass, similar to the green roof alternatives S6 and S7, where anthemis tinctoria and lawn grass were used. With the application of lower greenery, the results of both studies are comparable.

According to a study by Scolaro et al. some of the studies reported so far do not include the load-bearing layer in the life cycle assessment of a green roof (Scolaro et al., 2022). The supporting structure is responsible for the largest impacts in most of the impact categories evaluated and should therefore be an integral part of this evaluation. Considering all layers of the green roof system would facilitate comparison of results between studies. At the same time, while it is important to evaluate individual wells of the green roof system, the result is that the entire green roof composition is evaluated as part of a comprehensive building assessment. It is also important to include the proportion of material of each layer in the composition, which determines the resulting emissions from the green roof layers. For this reason, it is important to assess all layers in the quantities in which they are actually designed in practice.

3.3. Multicriteria analysis

The results of the multicriteria analysis are presented in the Figure 9 - Figure 12. Based on the multicriteria analysis, the most optimal composition was shown to be S8, which came out best in three of the four evaluation criteria (IPA, WSA and TOPSIS). In the fourth criterion (CDA), the composition of S9 was ranked best.

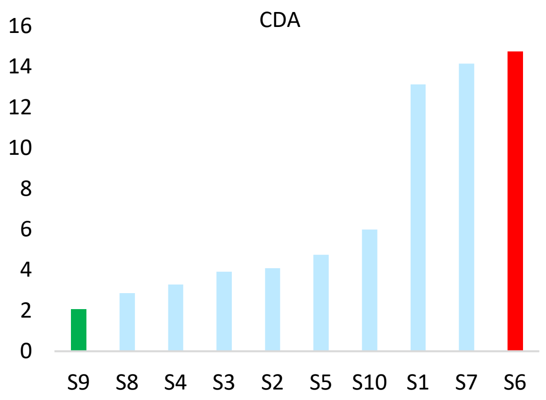

Figure 9 Graphical interpretation of CDA results

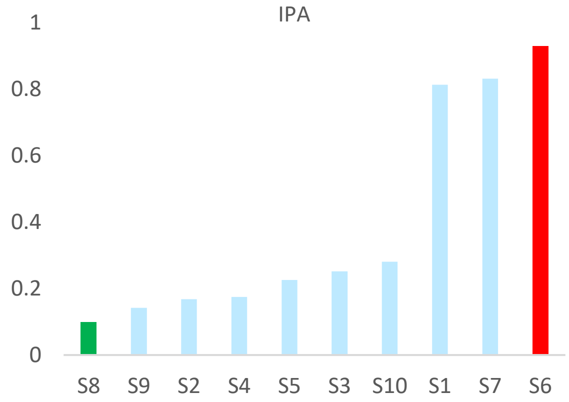

Figure 10 Graphical interpretation of IPA results

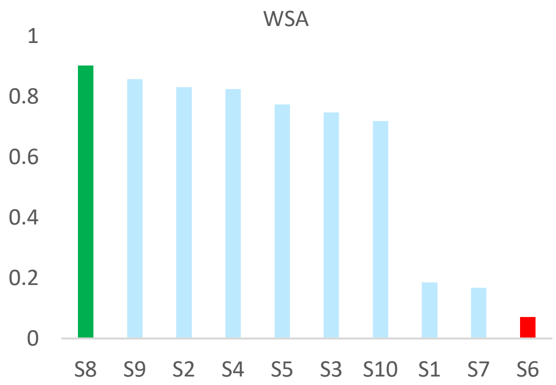

Figure 11 Graphical interpretation of WSA results

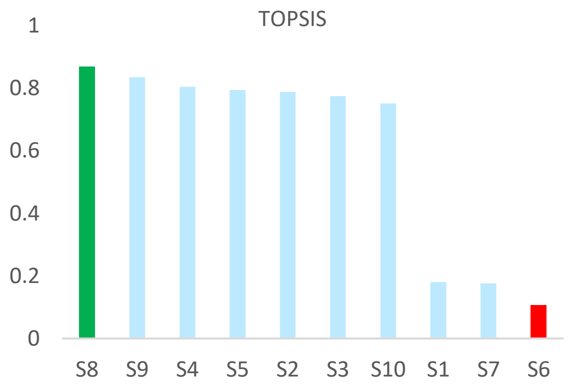

Figure 12 Graphical interpretation of TOPSIS results

Composition S8 was the most optimal option mainly because the composition did not use SBS modified asphalt-based material, which was used to produce waterproofing asphalt strips (SBS). The drainage layer in this composition was designed in EPS slabs, which emit 0.946 kg CO_{2e} during their life cycle, while the HDPE drainage layer, which was designed in the S3 composition variant, emits up to 29.38 kg CO_{2e}. For this reason, the S9 composition also revealed a lower negative environmental impact than the other compositions. In terms of overall global warming potential, composition S8 produced the least CO_{2e} emissions. In compositions S8 and S9, high-intensity foliage, hawthorn and cherry were used, which, as shown by the GWP-bio indicator, reduced carbon emissions the most. In the life cycle cost assessment, composition S8 demonstrated similarly low costs as compositions S3, S4 and S5. The operational energy module B6 achieved the highest economic burden of 306.42€ (60.49%) for green irrigation. The least optimal compositions were found to be S6 and S7, where SBS-based asphalt strips were used. The low green space proposed here also showed a higher life cycle cost for module B6 of 612.84€ (69.76%). The operational energy module considers the fact that low vegetation, unlike high vegetation, needed irrigation at more frequent intervals (Schweitzer et al., 2014). The methodology proposed in the Lisbon Green Roof Study enabled the improvement of strategic investment decisions through an economic evaluation of the installation of green roofs. The authors concluded that green roofs were a feasible solution for highly urbanized areas such as Lisbon (Teotónio et al., 2018). Teotónio et al. in another study followed up on the evaluation of green roofs.

The paper presents an application to a case study in Lisbon, where the installation of six different green roofs was compared. The aim of this study was to adapt existing multicriteria decision models to the context of green roof installation (Teotónio et al., 2020).

The construction of green roofs manifested a beneficial effect on the environment, increasing the amount of oxygen in the air, reducing CO_2, reducing dust, reducing noise levels, and absorbing up to 50% of rainwater, where its subsequent evaporation through the surface humidified and cooled the surrounding air. In addition, green roofs increased the rating of buildings assessed according to comprehensive environmental criteria (Berndtsson et al., 2006; Olszowski, 2016; Suszanowicz et al., 2019).

3.4. Sensitivity analysis

Sensitivity analysis was applied to determine the impact rate of climate zone changing on GWP-total and life cycle costs. Four green roof compositions designed for different climatic conditions were included in this analysis. For moderate zone conditions, the S8 composition was chosen as it showed the best results in terms of multicriteria analysis. This composition was subsequently modified to meet the thermal performance requirements (U-value) for cold and subtropical climatic conditions. The concrete floor slab, steel reinforcement, substrate and thermal insulation material have the greatest influence on the GWP-total at the system boundary for the A1-A3 product phases. Considering the influence of different climate zones, a sensitivity analysis was performed for the influence of the thickness of the thermal insulation material on the GWP-total. Table 2 showed the extent of the influence of the climate zone and therefore the influence of the thickness of the thermal insulation material on the GWP-total.

Table 2 Comparison of the environmental impacts (kg CO_{2e}) of the four climate zones and the difference of the moderate climate zone with the cold and the two subtropical zones (%)

Climate zone	Moderate climate (U=0.1 W/m²·K)	Cold climate (U=0.09 W/m²·K)	Difference %	Subtropic climate 1 (U=0.32 W/m²·K)	Difference %	Subtropic climate 2 (U=0.75 W/m²·K)	Difference %
Thickness mm	320	280		20		0	
XPS insulation (A1-A3)	21.06	24.06	12.47%	1.5	-92.88%	0	-100%
Assembly S8 (A1-A3)	168.5	171.51	1.75%	148.94	-11.61%	147.44	-12.50%
Assembly S8 (A-D)	445	435	-2.24%	471	5.84%	489	9.89%

Reducing the thickness of the thermal insulation material reduced the GWP-total of the S8 composition in the A1-A3 phase by 12% for subtropical climate zone 1 and 14% for zone 2. With the thickness of thermal insulation material, the GWP-total value of the composition increased by 1.8% for the cold climate zone. In the system boundary from "Cradle-to-Cradle", which included energy and water consumption for irrigation, there was a 2.24% reduction in GWP-total between the moderate and cold zones. Compared to the moderate zone, there was an increase of 5.84% in GWP-total for subtropical zone 1 and 9.89% for zone 2. From these findings, it can be concluded that the differences in GWP-total of the S8 composition when implemented in cold and subtropical climates are comparable. A given S8 composition is suitable for other climates if the variation of thermal insulation thickness and irrigation water consumption was taken into account. Designing suitable vegetation for local climatic conditions was important to guarantee sustainable green roofs. For the application of the proposed green roofs in different climatic conditions, vegetation capable of coping with more demanding climatic conditions was selected from the beginning in this study. By implementing the most optimal green roof variant (S8) in different climate zones, a negligible difference was found between cold, moderate and subtropical climate zones. Similarly, the comparison of the GWP of the proposed intensive roof with the results of the study of Pique et al. (436.7 and 435.0 kg CO_{2e}/m^2/50 years) for the cold climate zone showed minimal differences. In another study (Koroxenidis et al., 2021) for a subtropical climate zone, different types of green roofs, including intensive roofs, were evaluated. Emissions were assessed within the four climate zones of one country. The results showed that intensive green roofs produced more than twice the CO_2 emissions (889.125, 1016.75, 1024.375, 988.5 kg CO_{2e}/m^2/50 years) in all the zones evaluated, as the energy consumption of the building was included in the calculation. Gargari et al. calculated the CO_2 emissions (145 kg CO_{2e}/m^2/year) of an intensive green roof located in the subtropical zone. In this case, the low CO_2 emissions compared to the S8 assembly were caused by the non-incorporation of irrigation into the LCA (Gargari et al. 2016).

From studies of intensive green roofs and green roofs in general, the need to plant greenery typical for a specific climatic zone emerged. Whether it is a cold zone where plants have to withstand cooler conditions or a subtropical zone where plants are exposed to drought and higher temperatures. In addition, thermal requirements and the associated need to include/not include thermal insulation in the stress assembly play an important role. This study provides a proposal for the implementation of vegetation capable of surviving in more extreme conditions and at the same time sequestering carbon to such an extent as to compensate for the carbon emissions produced during the life cycle of the green roof.

Table 3 Comparison of the economic impacts (€) of the four climate zones and the percentage increase and decrease in costs of a moderate climate zone with a cold and two subtropical zones (%)

Climate zone	Moderate climate (U=0.1 W/m²·K)	Cold climate (U=0.09 W/m²·K)	Percentage increase and decrease %	Subtropic climate 1 (U=0.32 W/m²·K)	Percentage increase and decrease %	Subtropic climate 2 (U=0.75 W/m²·K)	Percentage increase and decrease %
Thickness mm	320	280		20		0	
XPS insulation (A0-A5)	26.00	23.01	-11.50	7.00	-73.08	0	-100
Assembly S8 (A0-A5)	160.00	590.00	268.75	318.00	98.75	82.00	-48.75
Assembly S8 (A-C)	585.00	1,115.00	90.60	1,765.00	201.71	1,652.00	18.39

In terms of cost in the A0-A5 phase for thermal insulation, the cost depends on the thickness of the material. When implementing the S8 composition in subtropical zone 1 the cost increased to 318€/m², in subtropical zone 2 it decreased to 82€/m² and in cold zone it increased to 590€/m². Considering all life cycle phases, there was an increase in life-cycle costs in all three scenarios compared to the moderate zone scenario. In terms of life cycle costs, the S8 variant was more expensive when implemented in other climate zones due to the inflation factored in.

To identify the uncertainty between the scenarios, the standard deviation was calculated. Figure 13 shows the variation between the scenarios from an environmental and economic perspective.

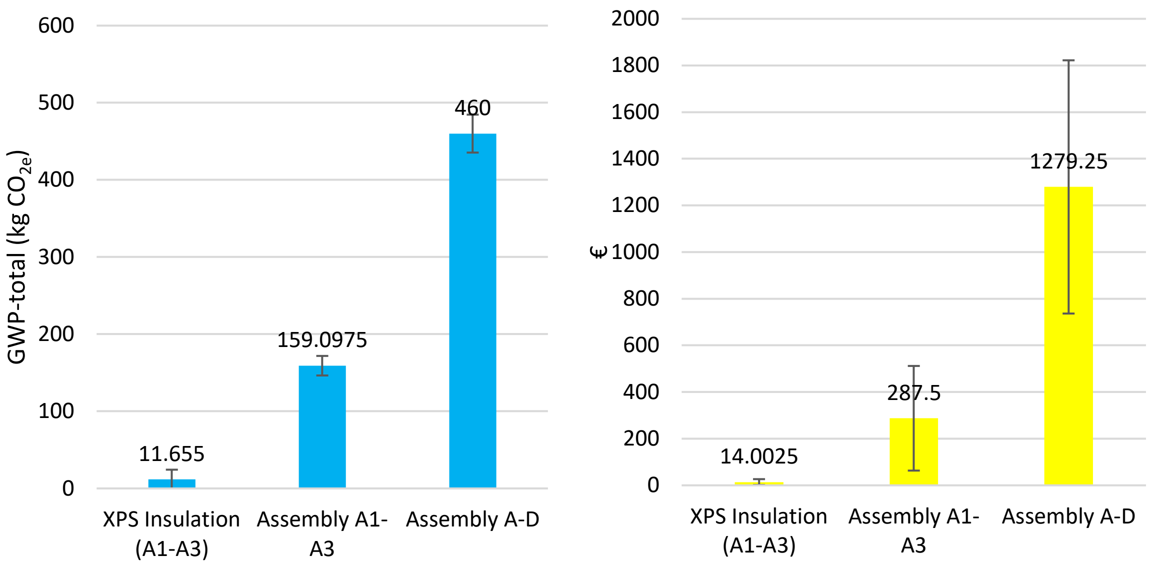

Figure 13 Variability between scenarios in environmental (on the left) and economic aspects (on the right)

From the uncertainty analysis, it was found that for environmental impacts, the standard deviation was low across all scenarios compared. It was 12.67 kg CO_{2e} for the XPS insulation in phases A1-A3, 12.67 kg CO_{2e} for the entire roof construction in phases A1-A3, and 24.58 kg CO_{2e} for the whole roof construction for phases A-D. A higher standard deviation was observed for the economic impacts. For the XPS insulation in phases A1-A3 it was 12.52 €, for the whole roof structure in phases A1-A3 it was 224.3 € and for the whole structure for phases A-D it was 542.79 €. The results show that the higher standard deviation is due to the different economic conditions and prices of materials in the evaluated areas (climate zones).

From the above it follows that changing the thickness of the thermal insulation does not affect the robustness of the analysis results. According to the analysis, the results of the environmental impacts are consistent and are not significantly affected by changes in the parameters of the base model. On the other hand, the results of the analysis of the economic parameters indicate that the results vary significantly, due to the different economic conditions in the countries considered.

4. Environmental strategies and policies

In practice, there is still little consideration of the environmental benefits and long-term impacts of sustainability. The EU is introducing new measures; from 2027 it will be mandatory to demonstrate reductions in environmental impacts by calculating the global warming potential for new large buildings and from 2030 for new buildings. The GWP of new buildings over their life cycle will have to be calculated from 2030 onwards in accordance with the Level(s) framework, thus providing information on emissions over the entire life cycle of new buildings. Life cycle emissions are particularly important for large buildings, so the obligation to calculate them applies to large buildings (with a useful floor area greater than 2,000 m^2) from 2027 onwards. Such proposed compositions and the calculation of their environmental impacts are of use and of great importance to the planners who will design the buildings and do these analyses. From the research, they will learn more about the environmental impact of materials and their thicknesses, the importance of plants, vegetation, and biogenic carbon in the built environment, and will receive guidance on designing intensive green roofs (European Commission, 2021; European Commission, 2022). The installation and subsequent maintenance costs of green roofs are higher in the early stages of the life cycle compared to conventional flat roofs, but this disadvantage is offset by the reduction in the building's energy consumption and the financial gains from the increased value of the property's sales potential (Ulubeyli, S et al., 2017). According to a study by Alekseeva et al. green roofs could become an integral element of green infrastructure in an urban area that currently lacks it. Green roofs are a means to increase the sustainability of cities. Several studies have shown that despite ambitious policy efforts to introduce green roofs in urban environments, there is still a sufficient number of implemented in many regions of the world. These efforts are supposed to be essential elements of green infrastructure to increase the sustainability of cities (Versini et al., 2020; Yuliani et al., 2020; Liberalesso et al., 2020). Many cities have policies in place to encourage the deployment of green roofs. Our approach could be part of a toolkit to help practitioners and policy makers select the appropriate materials and technologies according to local needs, regardless of the climate zone. For example, city governments can support the installation of green roofs in areas at increased risk of heat islands, due to climate change or lack of green space. These measures can help mitigate the impact of climate change and increase biodiversity in the city (study by Alekseev et al.). The approach used in this study is quite flexible and can be used to inform local governments about the identification of potential areas for the implementation of green roofs according to their individual needs.

The suitability of implementing intensive green roofs in urban areas in terms of their sustainability is still questionable. Few studies published so far have addressed a detailed life cycle assessment of intensive green roofs. Based on the results of our study, it can be added that the implementation of intensive green roofs in urban areas is important for the reduction of CO_2 and other greenhouse gas emissions. The study supports the return of green roofs to built-up urban areas. Especially the tall greenery typical for intensive green roofs sequesters more carbon compared to extensive green roofs with low greenery. In life cycle assessment, it is recommended to carry out a comprehensive environmental and economic assessment of all layers of the green roof from the load-bearing layer to the substrate, including the greenery. The load-bearing layer of the green roof and the substrate contribute the most to the environmental and economic impacts. However, the negative impacts from the load-bearing structure and substrate can be offset by appropriate choice of materials and planting of tall vegetation. These findings are of great importance in the context of climate change. From an economic point of view, the implementation of intensive green roofs is costly in the initial phases, but a return on investment can be achieved by reducing energy consumption during the operation and maintenance phases. Optimal design of intensive roof assemblies is environmentally suitable for implementation in different climatic zones, with only a small change in the thickness of the thermal insulation.

5. Limitations of the study

The limitations of this study included the omission of the social aspect of sustainability in the overall assessment of the roof compositions. Furthermore, the incorporation of recycled materials was not considered in the design of the green roof composition. The research focused only on the life cycle analysis of the different alternative technologies of intensive green roofs, while the compositions of extensive and conventional roofs were not considered. The study did not evaluate the impact of the green roof on the microclimate of the building. However, according to the articles available that also evaluated this impact, it appeared that the green roof had a positive effect on the microclimate of the building. The building does not overheat, therefore maintaining moderate indoor and outdoor temperatures (Beshir et al., 2018). Future research would also focus on evaluating this social factor, which was necessary for the sustainability of buildings. As a limitation, it is considered that primary data were not used in the study. The study is based on a database of data that is classified as secondary data. Benefits and loads beyond the system boundary (Module D) in the LCC were not included in the calculation.

6. Conclusion

In this study, ten alternative compositions of intensive green roofs were assessed based on their life cycle impact and life cycle cost, using a multi-criteria analysis to determine the most appropriate composition. Roof composition S8 was identified as the best alternative according to the analytical methods of IPA, WSA, and TOPSIS, and the second-best according to the CDA method.

Composition S8 included a reinforced concrete slab, a PE vapor barrier, PUR adhesive for thermal insulation, two layers of XPS-based thermal insulation boards, mechanical anchors for thermal insulation, PE separation foil, a PVC-P-based root-resistant waterproofing membrane, PES protective geotextile, an EPS-based drainage board, PP filter geotextile, and intensive roof substrate. The vegetation layer featured Hawthorn. This composition exhibited the lowest environmental impact in terms of global warming, acidification, ozone depletion, abiotic depletion of non-fossil resources, and water consumption. However, S8 was ranked fifth in terms of life cycle costs, approximately 450–500 €, nearly twice as high as the costs for compositions S1, S6, and S7.

The study suggested that S8 might be the optimal choice for intensive green roofs based on environmental impact and life cycle cost. However, factors such as aesthetics, maintenance requirements, and local climatic conditions also needed to be considered when selecting the best green roof composition for a specific building or site.

Life cycle analysis confirmed that building materials were a significant source of emissions released before their use. Vegetation, like trees, acted as natural carbon sinks through carbon sequestration. In the worst-case variant, S6, the GWP-bio contributed only 0.83% to the GWP, indicating minimal positive environmental impact. In contrast, the best variant, S8, due to the tall green vegetation (Hawthorn), had a GWP-bio contribution of up to 78.3%, showing a significant impact on CO_2 sequestration.

Further research aimed to emphasize the importance of vegetation in urban environments and the integration of green infrastructure into building designs to create sustainable environments and mitigate climate change effects. Sensitivity analysis results indicated that the S8 green roof composition was suitable for cold and subtropical regions in terms of GWP-fossil but not in terms of life cycle costs.

The design of the green roofs´ composition plays a key role in the process of their implementation in urban areas. This study aimed to assist interested parties in making informed decisions by providing a comprehensive assessment of the environmental and economic impacts of various green roof compositions. It also examined the adaptability of the optimal design across different climate zones. The findings suggested that the economic sustainability of intensive green roofs needed further optimization for different climate zones. From the above results, it is concluded that the applicability of the intensive green roof to different climate zones needs to be more thoroughly optimized from an economic aspect of sustainability.

Recommendations for future research

Currently, the use of LCA models is applied in all sectors of the economy as they simplify the decision-making process for the future use of green practices/products. LCA analytical tools allow to understand the impact of products from their extraction to the final stage, thus contributing to the promotion and adaptation of green practices for sustainable development at a global level. Future research could be extended to evaluate intensive, extensive and semi-intensive green roofs and compare them with conventional roofs in terms of all aspects of sustainability. The composition of the green roof would be adapted to different climatic conditions, whether cold, temperate or subtropical, by varying the thickness of the thermal insulation but also by investigating different types of materials. The research could also be extended to assess Module D (benefits and burdens beyond the system boundary) in the life cycle cost assessment following a circular economy approach. This will help contribute to the economic sustainability of green roofs. Additionally, future research should further focus on the LCA of each layer of the green roof in relation to the wider application of natural materials. In this way, a reduction in environmental impact in the production of building products. As part of the research, the authors propose to investigate other elements of green infrastructure (green façade) in combination with renewable energy sources.

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