Arch. Min. Sci. **69** (2024), 2, 327-347

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI: https://doi.org/10.24425/ams.2024.150348

KATARZYNA KRYZIA[1*], ALEKSANDRA RADZIEJOWSKA[1],
ANNA SOBOTKA[1*]

ANALYSIS OF FACTORS INFLUENCING CARBON FOOTPRINT REDUCTION IN CONSTRUCTION PROJECTS

Abstract. This article addresses the issue of reducing carbon footprint in construction production. It focuses on the sources and factors of greenhouse gas emissions responsible for climate change. The construction sector plays a significant role in generating carbon footprint, both in the manufacturing of construction products within supply chains and during the execution of construction work on-site. The identified factors that influence carbon footprint throughout the lifecycle of a construction project and the life of a building are examined and analysed using the DEMATEL method. The research aims to identify causal relationships among factors that contribute to minimising carbon footprint in construction projects. The factors with the highest causal impact are identified in each phase of the building's lifecycle, including Building Information Modelling (BIM), appropriate selection of construction products, and regulatory and financial incentives. The results of the analysis can be utilised to support decision-making processes aimed at reducing harmful emissions during project realisation and building operation.

Keywords: carbon footprint; construction project; DEMATEL method; causal-effect analysis

1. Introduction

The adverse effects of climate warming are largely attributed to the emission of greenhouse gases, primarily carbon dioxide and methane, nitrous oxide, and other greenhouse gases (*ISO 14067:2018(en), Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification*, n.d.) [1]. The total emissions of these gases (directly or indirectly caused by individuals, organisations, events, or products) are referred to as the carbon footprint,

---

[1] AGH UNIVERSITY OF KRAKOW, FACULTY OF CIVIL ENGINEERING AND RESOURCE MANAGEMENT, AL. MICKIEWICZA 30, 30-059 KRAKOW, POLAND

* Corresponding author: kryzia@agh.edu.pl; sobotka@agh.edu.pl

expressed in carbon dioxide equivalent (CO_2). Climate change is not only caused by industry, transportation, and waste, but also by deforestation, expansion of agricultural and animal farming areas, extensive urbanisation, and unsustainable transportation. Climate changes are induced by all sectors and branches of the economy to varying degrees. Climate warming is occurring so rapidly that it is now crucial not only to prevent global warming but also to minimise its effects.

Among the largest sources of greenhouse gas emissions globally, carbon dioxide is mentioned overwhelmingly, constituting almost 80% of the total emissions. The European Union, among other regions/countries worldwide, is one of the largest emitters of greenhouse gases, although visible attempts at reduction are evident. The construction sector plays a significant role in both EU and global greenhouse gas emissions. According to data from [2], it accounts for approximately 40% (around 20 billion tons of CO_2 in 2020). Despite improvements in building energy efficiency, total emissions related to construction are still increasing due to increased demand for floor space, construction materials, thermal insulation, etc. In construction production, two types of carbon footprint are distinguished: operational and embodied. The operational carbon footprint mainly results from the use of the building and accounts for approximately 60-70% of the total carbon footprint of the building. It includes energy consumption for heating, cooling, hot water preparation, lighting, ventilation, and air conditioning. On the other hand, the embodied carbon footprint accounts for the remaining 30-40% of the building's carbon footprint and arises from greenhouse gas emissions associated with the production of building materials and construction processes [3]. The analysis of the total carbon footprint in construction is based on an integrated approach, encompassing all sources and factors, as well as the life stages of the building that impact CO_2 emissions [4]. The development of technologies aimed at reducing the energy consumption of buildings during their operation highlights the significance of the embodied carbon footprint and the possibilities for reducing its emissions in the production processes of construction products, construction technologies, construction work technologies, and construction organisation (building projects), also considering other aspects of sustainable development. The comprehensive assessment of a building's environmental impact is conducted using the Life Cycle Assessment (LCA) method according to the standard [5] linked to the standard [6], which also includes other aspects related to sustainable development, such as the social and economic properties of buildings. The guidelines contained in these standards can be applied to assess CO_2 emissions throughout *The Whole Life Carbon* (WLC) cycle [7]. The importance of the construction sector in achieving climate neutrality is indisputable [4]. Therefore, the problem of reducing the carbon footprint in construction projects is highly significant and urgent.

Systematising the factors influencing the minimisation of the carbon footprint in the creation and existence of buildings is the subject of research presented in this article. The authors focus on compiling factors related to the carbon footprint and subsequently analysing them. Through the use of methods such as DEMATEL, causal relationships between factors conditioning the minimisation of the carbon footprint in construction projects throughout the building's lifecycle have been identified. The obtained results should be taken into account in managing activities and production in the construction industry at various decision-making levels and in processes related to the production of construction products, urban planning, architecture, building technology, work organisation, and supply chains.

2. The issue of carbon footprint in construction in the context of EU directives

2.1. Fundamental issues related to the carbon footprint

Carbon footprint is defined by various organisations, legislative institutions, and scientists. It is typically referred to as Global Warming Potential (GWP), which represents the potential for creating a greenhouse effect. It is the sum of emissions of all greenhouse gases caused by a specific process, system, or population, taking into account their absorption and storage within specified boundaries. It is expressed in kilograms of carbon dioxide equivalent (CO_2eq) per functional unit (characteristic) of a product [3,8].

Carbon footprint, referred to as the Carbon Footprint of a Product (CFP), is the total amount of emitted carbon dioxide and other greenhouse gases (GHGs) relative to the emissions resulting from the life cycle of a given product while considering its storage and disposal processes [9-12].

According to the (*ISO 14067:2018(en), Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification*, n.d.) [1] the carbon footprint of a product is the sum of GHG emissions and absorption expressed in carbon dioxide equivalent. It is based on a life cycle assessment, using a specified climate change impact category.

In addition to CO_2, other greenhouse gases (according to the Kyoto Protocol [13] include nitrous oxide/nitric oxide (N_2O), methane (CH_4), and fluorinated industrial gases (hydrofluorocarbons (HFCs), sulphur hexafluoride (SF6), perfluorocarbons (PFCs)). Each of these gases can be assigned a *global warming potential* (GWP) indicator, which numerically indicates their climate warming impact compared to the warming potential of 1 kilogram of carbon dioxide over a century [14].

The methodology for determining the carbon footprint has not yet been unambiguously regulated at the global level. Therefore, there are many issues regarding measurement methods that differ. The first issue concerns the scope of analysis, as it is possible to measure both direct emissions associated with the analysed object and indirect external emissions that occur outside of it but affect its functioning. Another issue concerns the selection of greenhouse gases and the determination of the system boundaries that are subject to analysis. Emissions can be examined over a specific period or emissions related to the entire life cycle of the analysed object [10,15-17].

The carbon footprint measurement procedure is based on the product life cycle (*Life Cycle Analysis*, LCA) and is standardised by the ISO 14040 series. This method allows for obtaining a quantitative result regarding GHG emissions by considering a broader range of product environmental impacts (many environmental issues) – the carbon footprint is treated as part of LCA analysis. The full life cycle of a specific product includes the processes of raw material extraction, production and transportation, proper use, and final storage or economic utilisation. Depending on the purpose of the calculations, the scope of the life cycle analysis may vary. Typically, the total greenhouse gas emissions during the full product life cycle are calculated (*from cradle to grave*) for companies or for a shorter period (*from cradle to gate*) for specific products [9,10,12,14].

2.2. Actions taken in the EU to minimise the carbon footprint

The European Union has set the goal of decarbonising the economy and achieving full climate neutrality by 2050. Key to this goal are the construction and real estate sectors, which account for 36% of greenhouse gas emissions related to energy consumption in the EU. In terms of the facts presented, the methodology for determining the carbon footprint of the construction industry is crucial [7].

The European Union has set an ambitious goal of climate neutrality by 2050 through a gradual reduction of greenhouse gas emissions. To achieve this, the EU is implementing and continues to introduce various strategies in the field of energy and climate policy. Among them, according to [4], the following initiatives can be highlighted: European Green Deal [18], Renovation Wave [19], and Plan REPowerEU [20].

The European Green Deal action plan [18] encompasses a package of legislative proposals adopted by the European Commission to align the EU's climate, energy, transport, and taxation policies with the goal of achieving a net reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990 levels. The proposals outlined in [18] include, among others, renovations. The fund aims to provide an estimated amount of 72.2 billion euros over a period of 7 years to finance building renovations, promote zero-emission and low-emission mobility, and even support income. In addition to residential buildings, it will be necessary to renovate public buildings to make better use of renewable energy sources and improve energy efficiency [18]. The European Commission proposes in [18] to obligate member states to renovate at least 3% of the total area of all public buildings annually, set a target of 49% renewable energy use in buildings by 2030, and require member states to increase the use of renewable energy for heating and cooling buildings by 1.1 percentage points annually, up to 2030.

The aforementioned directives refer to and update the European Commission's adopted strategy, *The Renovation Wave* [19], established in 2020. This strategy aims to support new investments in the long term, starting with public and less energy-efficient buildings, stimulate digital transformation, and create employment and growth opportunities throughout the renovation supply chain. The document calls for at least doubling the annual rate of energy renovation for residential and non-residential buildings by 2030 and supporting deep energy renovations. Mobilising efforts at all levels to achieve these goals will lead to the renovation of 35 million building modules by 2030. To achieve climate neutrality across the EU by 2050, it will also be necessary to maintain an increased pace and deepened scope of renovations beyond 2030 [19].

Furthermore, *The Fit for 55* package transforms the vision outlined in the European Green Deal [20] into concrete regulations for the climate objectives of the European Union. Its aim is to reduce carbon dioxide emissions by 55% by 2030 compared to 1990 levels. The ultimate goal is climate neutrality by 2050. *The Fit for 55* package emphasises the crucial role of electrification based on renewable energy sources, particularly through the promotion of heat pumps in buildings.

On May 18, 2022, the European Commission issued a communication to the European Parliament, the European Council, the European Economic and Social Committee, and the Committee of the Regions called *The REPower Plan*. The plan aims to rapidly reduce our dependence on Russian fossil fuels by accelerating the transition towards clean energy and achieving a "true" energy union [20].

Governments, non-governmental organisations, and representatives from the industry and business sectors are therefore taking initiatives to reduce greenhouse gas emissions. These actions include continuous monitoring, reporting, verification, and forecasting of the climate change impacts [8].

2.3. Carbon footprint minimisation in Poland

Entrepreneurs worldwide, including in Poland, are deciding to calculate their carbon footprint for various reasons. Firstly, this is driven by market requirements – companies that collaborate with international partners often need to provide the carbon footprint value of their products. Polish businesses learn about the need for calculating this indicator from their Western business partners, who demand carbon footprint information in their tender inquiries. To participate in tenders, Polish companies must calculate the carbon footprint value for their products. Secondly, there is a reporting obligation to the Carbon Disclosure Project (CDP) – an international non-profit organisation that enables companies to calculate, disclose, manage, and share their environmental performance information and achievements in greenhouse gas emissions reduction. Thirdly, calculating the carbon footprint is often required by Corporate Social Responsibility (CSR) and non-financial reporting. Embracing the CSR concept means that businesses not only comply with legal and formal requirements but also invest in human resources, environmental protection, and building positive stakeholder relationships [8].

In Poland, there are no regulations in national legislation that require the calculation of the total carbon footprint of buildings throughout their life cycle. Therefore, the basis for taking action must be changes in legislation that enable the implementation and verification of activities related to reporting CO_2 emissions in the construction sector [4]. In Poland, many scientific communities, governmental and local institutions, non-governmental organisations, and businesses are considering standardising the methodology for calculating the carbon footprint of buildings throughout their life cycle. An example of such efforts is the report "*Zero Carbon Footprint of Buildings. Roadmap for Decarbonizing the Construction Industry by 2050*", published by the Polish Green Building Council (PLGBC) in June 2021 [4]. The report emphasises that achieving a net-zero total carbon footprint for buildings by 2050 is a very ambitious yet achievable goal. However, it requires transformation in both buildings and the entire construction sector [4]. The report [4] presents actions that all stakeholders associated with the building sector should implement by 2050 to realise the following vision: all buildings should have a zero operational carbon footprint, while new and renovated buildings should have a net-zero carbon footprint throughout their life cycle (meaning a balance between embodied carbon and operational carbon footprint). The report [4] showcases the most advanced European countries in terms of regulations concerning the analysis of greenhouse gas emissions throughout the life cycle (*Whole Life Carbon* – WLC) (Denmark, Finland, France, the Netherlands, and Sweden) and suggests that legal provisions addressing the building carbon footprint beyond operational energy or operational carbon footprint are feasible and can be implemented in national legislation.

Currently, there is no requirement in Poland for conducting life cycle assessment analyses of buildings. They are not standard practice for investors and designers. Typically, such assessments are only prepared for the purpose of multi-criteria certifications such as BREEAM (*Building Research Establishment Environmental Assessment Method*), LEED (*Leadership in Energy and Environmental Design*), ZIELONY DOM, etc., and are carried out by specialisedoffices based on the design. However, the greatest potential for optimization and CO_2 emissions reduction lies in the conceptual phase [4].

2.4. Analysis of the global literature on carbon footprinting

In both Polish and international research literature, there is a growing interest in the issue of carbon footprint [21-26], methods for calculating it using computer programs [27-31], and examples of such analyses [32-41]. This trend encourages a closer look at publications in this field.

In the context of research on the importance of the carbon footprint, D.Z. Li and co-authors [10] point out that residential buildings account for a large share of global carbon emissions, while they play important roles in economic growth and social development at the same time. Therefore, the appropriate evolution routes of residential buildings need to balancetheir carbon emission and value creation. Authors estimate carbon emissions based on energy and resource use at each stage in the life cycle of a residential building.

L. Huang and co-authors [36], analysing CO_2 emissions in the global construction sector, identify that emerging economies, particularly China, account for a significant portion of the sector's emissions. Their study highlights the higher emission intensity in developing countries. They point out that promoting the development and use of low embodied carbon building materials and services, the energy efficiency of construction machines, as well as renewable energy use are identified as three main pivotal opportunities to reduce the carbon emissions of the construction sector.

Also, E. Heffernan, W. Pan, X. Liang and P. De Wilde [37] addresses the challenges facing the construction industry, analyzing the barriers to building zero carbon emission homes in the UK. They point out obstacles related to legislation, economics, and the lack of appropriate skills, while also proposing solutions to support the transition to low-emission construction.

Research by J. Zuo, B. Read, S. Pullen, and Q. Shi [38] focused on examining the associated carbon-neutral commercial building developments. The paper highlighted factors that contribute to or impede the implementation of carbon neutral commercial building developments. The results showed that the lack of a clear definition of carbon neutral building presents a significant barrier in pursuit of this goal.

J. Li and M. Colombier [39] analyses the impact of energy efficiency in buildings on carbon dioxide emissions management in China, highlighting its significance in the context of mitigating climate change. Their approach suggests that comprehensive strategies involving building design, urban planning, and the construction materials industry can significantly contribute to improving energy efficiency, which is crucial for rapid urban growth. They point out that a coherent institutional framework needs to be established to ensure the implementation of efficiency policies.

R. Geryło and A. Garbacz [21] discusses the challenges and opportunities for sustainable development in the construction industry in light of climate change, emphasising the need for a paradigm shift towards sustainable construction practices.

The main purpose of the study by T.C. Kuo [31] was to construct a collaborative design framework to help enterprises collect and calculate products' carbon footprints in a readily and timely manner throughout the entire supply chain. In this research, a computer-aided tool was used to integrate enterprises' internal systems with the life cycle inventory database and to establish enterprises' GHGs bills of material system.

In paper P. Łasut and J. Kulczycka [28] presented a review of international and Polish programs calculating carbon footprint. They were divided into three groups, i.e. available online and computing a direct impact on the environment, counting direct and indirect effects, and lastly specialised programs. By analysing them, the strengths and weaknesses of each were identified.

A study was made of the consistency in all the selected calculators with respect to carbon footprint from emissions into the atmosphere.

Examples of carbon footprint analysis in the context of various aspects of construction and infrastructure constitute an important element of research.

Z. Karaczun, A. Kassenberg, and P. Siwicki [32] conducted a detailed analysis of the carbon footprint associated with the expansion of a waterway in the middle section of the Oder River. Their study included the methodology and scope of CO_2 emissions calculations, taking into account the use of concrete and steel, the number of machine hours required for construction and dredging of the riverbed, and the impact on the biologically active surface. This comprehensive assessment highlights the importance of a holistic approach to estimating the environmental impact of investments.

In article [17] A. Tažiková and Z. Struková presented a possible methodology to calculate construction and environmental costs in the project planning phase in the conditions of the Slovak Republic. Putting the methodology into practice has the potential to make it possible to reduce the carbon footprint. The authors indicate that the selection of building materials in the project planning phase is considered to be one of the actions. When choosing a building material, the client will decide not only on the construction cost but also on the environmental cost of building materials.

D. Wieczorek and K. Zima in paper [30], carried out a detailed analysis of the impact of the choice of construction materials and transport methods on the cost of road projects and the size of the carbon footprint. According to the authors, it is worth considering and proposing the necessary changes to the legal basis, which will pay attention to the need to consider not only cost criteria but also those related to reducing greenhouse gas emissions.

Z. Yeo, R. Ng and B.Song in study [33] streamlined technique is proposed to minimise the efforts required by the practitioner to obtain the embodied carbon footprint. The proposed technique comprises a probabilistic model of emission factor estimators used to estimate the required embodied emissions based on the four projects presented as case studies.

S. H. Teh and co-authors [34] as part of the project investigate the potential use of Engineered Wood Products (EWPs) and evaluate construction material replacement scenarios at the economy-wide scale in Australia. The main objective of the replacement scenario analysis was to assess the potential reduction in future GHG emissions by replacing the use of reinforced concrete with EWPs. The selection of low-carbon and sustainable building materials is crucial in reducing the built environment's carbon footprint.

W. Huang and co-authors in paper [16] study and develop a calculation methodology for carbon footprint accounting of urban buildings by taking Xiamen as a case study. Authors indicate that the implementation of low-carbon strategies in the building sector, such as increased energy efficiency design for new buildings and energy-saving retrofit for existing buildings, would have a significant influence on carbon emission reduction.

The study by S.S. Ramachanderan, V.K. Venkiteswaran and Y.T. Chuen [11] aims to identify and discuss the Green House Gas (GHG) emission reduction through Green Rating Tools in Malaysia in recognition of the environmental and economic threats posed by climate change. Research shows that it is certified through Green Rating Tools (GRT) to establish energy savings and GHG emission reductions.

T. Jafary Nasab and others in study [40], examined the carbon footprint of a residential tower in the Tehran Metropolitan City in the construction phase with the life-cycle approach. The article assessed all sources of carbon emissions in the construction phase, including emissions from manufacturing and extraction of building materials, transportation of building materials, construction equipment, vegetation cover around the building, and transportation of construction waste.

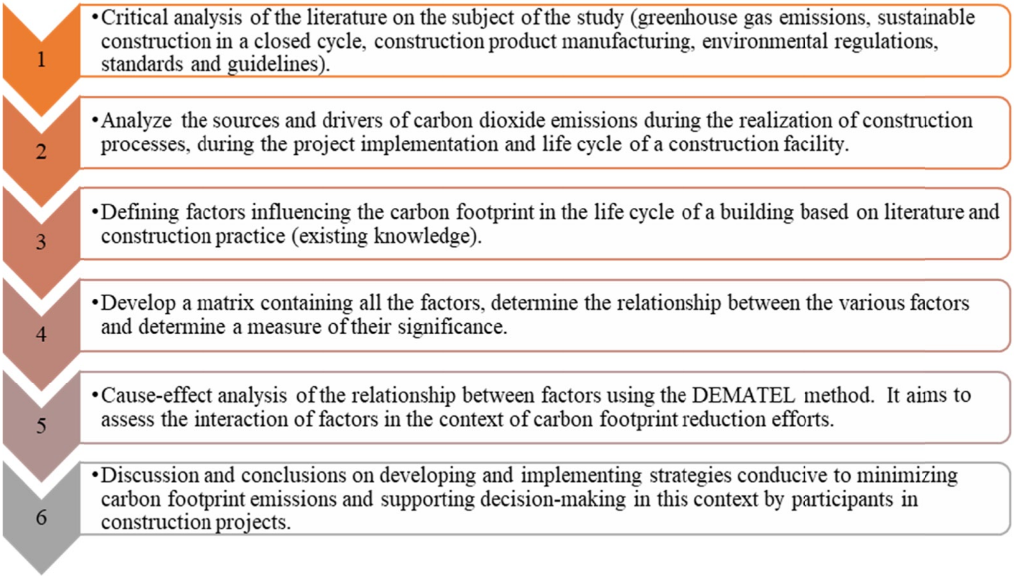
S.Y.C. Yim, S.T. Ng, M.U. Hossain and J.M.W. Wong in article [41] points out that there is still a lack of comprehensive investigation in analysing buildings' life cycle greenhouse gas (GHG) emissions, especially in high-density cities. In the paper, they take studies that have made attempts to evaluate GHG emissions by considering the whole life cycle of buildings in Hong Kong. In their research, they note that knowledge of localize demission at different stages is critical, as the emission varies greatly in different regions. Without a reliable emission level of buildings, it is difficult to determine which aspects can reduce the life cycle GHG emissions.

These diverse studies reveal the complexity of challenges associated with reducing the carbon footprint in construction and infrastructure, emphasizing the need for integrating methodologies, innovative techniques, and green strategies to achieve sustainable development.

3. Research methodology

3.1. Sequence of research

Studies to indicate the analysis of the impact of factors affecting the minimisation of carbon footprint in construction projects were performed in the following order (Fig. 1).



1 •Critical analysis of the literature on the subject of the study (greenhouse gas emissions, sustainable construction in a closed cycle, construction product manufacturing, environmental regulations, standards and guidelines).

2 •Analyze the sources and drivers of carbon dioxide emissions during the realization of construction processes, during the project implementation and life cycle of a construction facility.

3 •Defining factors influencing the carbon footprint in the life cycle of a building based on literature and construction practice (existing knowledge).

4 •Develop a matrix containing all the factors, determine the relationship between the various factors and determine a measure of their significance.

5 •Cause-effect analysis of the relationship between factors using the DEMATEL method. It aims to assess the interaction of factors in the context of carbon footprint reduction efforts.

6 •Discussion and conclusions on developing and implementing strategies conducive to minimizing carbon footprint emissions and supporting decision-making in this context by participants in construction projects.

Fig. 1. Methodology of proceeding in the identification of factors influencing the minimisation of the carbon footprint in construction projects. Source: own elaboration

3.2. Factors affecting CO_2 reduction in construction projects

Factors influencing the reduction of CO_2 emissions in construction projects should be considered in relation to each stage of the building's life cycle. The figure 1 presents the basis for constructing the set of factors for analysis. For this purpose, the authors conducted a critical analysis of the literature, an analysis of sources, and factors influencing carbon dioxide emissions throughout the life cycle of building objects based on both available literature and their own construction practice. By utilising the guidelines of the standard [5], experiences from multi-criteria certifications, and analysing the carbon footprint estimation methodology presented in reference [4], factors affecting the carbon footprint reduction in construction projects can be categorised based on the following phases (TABLE 1):

1. Preparation/Production/Design Phase – this stage involves developing concepts and construction designs, selecting construction technologies and materials, obtaining required permits and approvals, and preparing financial arrangements.
2. Execution/Construction Phase – this stage entails implementing the construction project by selecting construction methods, transporting construction materials to the construction site, and ultimately constructing the building itself.
3. Operation/Utilisation/Operational Phase – this stage involves the building being used according to its intended purpose. Regular maintenance and repair work, energy resource management, and maintaining high operational quality are necessary during this phase.
4. Demolition/Disposal Phase – this stage involves the safe demolition and disposal of the building in an environmentally friendly manner. This process requires specialised knowledge and skills, as well as adherence to specific standards and regulations.

TABLE 1

Factors affecting carbon footprint reduction in construction projects

Preparation/Production /Design Phase		**Execution/ Construction Phase**		**Operation/ Utilisation/ Operational Phase**		**Demolition/ Disposal Phase**	
A_1	selection of material production technologies	B_1	transportation of construction products to/from the construction site	C_1	economical use of the facility (energy, water, sewage, waste consumption)	D_1	liquidation technology
A_2	extraction of raw materials						
A_3	transportation of raw materials to the production plant or to the construction site	B_2	technology of works (construction)	C_2	maintenance of facilities during their use	D_2	waste management technology (segregation, transportation, recycling, etc.).
A_4	production of construction products on site	B_3	the use of machinery	C_3	the way of repairs, adaptations, upgrades, renovations		

TABLE 1. Continued

A_5	the way construction products are manufactured in the context of primary energy	B_4	type of equipment used	C_4	finishing systems and facilities equipment	
A_6	location of the investment in terms of accessibility to technical infrastructure	B_5	type of materials used	C_5	increasing the comfort of the facility	
A_7	location of the investment in terms of public transport accessibility	B_6	internal construction logistics	C_6	logistics of the facility environment	
A_8	location of the investment on the plot (sun exposure, shelter from the wind, etc.).	B_7	work efficiency (selection of work teams, size)	C_7	execution of thermo-modernisation	
A_9	functional layout of the building in terms of energy efficiency	B_8	workers' travel to the site/choosing a local company	C_8	regulations and legal restrictions	
A_{10}	design that takes into account the minimisation of construction activities during the operational phase (in the context of the maintenance of the facility and changing user requirements)	B_9	minimisation of construction waste	C_9	recommendations/ social awareness of building users	
				C_{10}	increase awareness of the need and usefulness of energy certificates and energy labelling of building products for building owners in energy efficiency	
A_{11}	application of BIM					
A_{12}	application of intelligent systems in building structures					
A_{13}	the use of closed media circuits (water, heat, etc.)			C_{11}	implementation of a (mandatory) multi-criteria certification system for buildings	
A_{14}	energy-saving installations (sanitary, heating, electrical, air conditioning)			C_{12}	supporting society with additional tax schemes and financial incentives that reduce emissions	
A_{15}	durability of products and systems used in the construction object					
A_{16}	quality of construction projects in terms of thermal protection					

Source: own elaboration

4. Identification of cause-and-effect relationships and their analysis

4.1. Method of identifying cause-and-effect relationships

In the scientific literature, various methods of causal analysis can be found. The most commonly used ones include the Ishikawa diagram and the cause-and-effect tree, which primarily focuses on identifying one-way relationships. Statistical methods such as regression or correlation analysis are subsequently applied, but these methods rely on data analysis and mathematical modelling. On the other hand, the DEMATEL method allows for the inclusion of expert assessments and subjective opinions in the analysis process, which can be important in cases where numerical data is lacking, as in the presented issue in the article. Additionally, it enables the consideration of mutual dependencies, graphical representation of results, evaluation of influence and dependencies, and facilitates multi-criteria assessment. Therefore, to identify causal relationships in the presented issue, the authors suggest utilising the DEMATEL method [42-46].

The procedure in the method will consist of the following steps [47]:

1. Identification of the set of factors influencing the carbon footprint in construction projects;
2. Development of a direct influence chart, which allows for expressing the directional impact of the considered factors on each other in a cause-and-effect context. A scale with parameter values $N = 3$ (where: 0 – no influence, 1 – weak influence, 2 – moderate influence, 3 – strong influence) was used to assess the "strength" of each factor's impact. The values of direct influence relationships within each pair of factors were determined based on the assessment made by the authors;
3. Creation of a matrix of direct mutual influence A_D based on the dependencies determined using the graph;
4. Determination of the normalised matrix of direct influence A'_D, which includes all parameters taking values in the range [0,1]. The normalisation factor (n) is assumed to be the largest sum of rows or columns in the matrix A_D:

$$A'_D = \frac{A_D}{n} \tag{1}$$

$$n = \max\left\{\sum_{i=1}^{n} a_{ij}; \sum_{j=1}^{n} a_{ij};\right\} \tag{2}$$

5. It is also possible to develop an indirect impact matrix ΔT:

$$\Delta T = A'^2_D \cdot \left(I - A'_D\right) \tag{3}$$

6. Determination of the total impact matrix T:

$$T = A'_D \cdot \left(I - A'_D\right) \tag{4}$$

7. On the basis of the above matrices, the indexes of positions and relationships are determined, respectively, which express in turn:
   - s^+ – refers to the role of a given factor in the process of determining the structure of links between objects,
   - s^- – expresses the total effect of a given factor on the others.

These values are determined according to the formulas:

$$s^+ = \sum_{j=1}^{n} t_{ij} + \sum_{j=1}^{n} t_{ji} = R_{T_i} + C_{T_i} \tag{5}$$

$$s^- = \sum_{j=1}^{n} t_{ij} - \sum_{j=1}^{n} t_{ji} = R_{T_i} - C_{T_i} \tag{6}$$

When these values are plotted on a graph, it is easy to see which factors have the greatest impact on the others and to determine which are causes and which are effects of the actions taken.

Finally, the net impact value is also determined, which tells which factor has the greatest impact on the others, taking into account both the causal and effect nature (TABLE 2):

$$\text{netto} = s^+ + s^- \tag{7}$$

The frequently used DEMATEL method is based on pairwise comparisons, similar to the decomposition in the Analytic Hierarchy Process method [48]. However, in this case, the direct mutual influence of the analysed factors on each other is examined. In this method, a discrete scale is also used for comparisons, with an arbitrary number N, where lower values of N indicate a smaller influence of one factor on another. Importantly, feedback loops can be analysed, which reflects the real relationships between factors. In the analysed problem, a classical 4-point scale used in the DEMATEL method was chosen, and mutual relationships, often exhibiting feedback, were established.

In the analysed problem, it was decided to consider the 4 phases of the life cycle of a construction project and align the criteria that will influence the possibility of reducing the carbon footprint. The authors presented a cause-and-effect analysis of carbon footprint reduction for the entire life cycle of the construction project, identifying the factors with the greatest impact on others and determining their nature. Additionally, the authors decided to separately analyse the cause-and-effect relationships for each phase. However, due to the limited scope of the article, only partial calculations and resulting charts were presented for Phase 2 and for the entire life cycle of the project.

4.2. Research results and their analysis

TABLE 2 presents the developed matrix containing all the factors, along with the determination of relationships between individual factors and the assessment of their significance. In this matrix, the values represent the following relationships between factors: 0 – no influence; 1 – small influence; 2 – moderate influence; 3 – significant influence. For example, we can interpret that A_1 – selection of production technology for materials has no influence (value of

TABELA 2

Direct impact matrix A_D where: 0 – no impact; 1 – low impact; 2 – medium impact; 3 – high impact

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	D1	D2
A1		0	0	1	2	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1
A2	2		3	1	2	0	0	0	0	0	0	0	0	0	1	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	1	0		1	2	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	2	0	1		3	2	0	0	0	0	0	0	0	0	2	0	3	2	2	2	2	2	3	0	3	0	0	1	1	0	0	0	0	0	0	0	0	0	1
A5	3	1	1	1		1	0	0	0	1	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	2	0	0	3	2		0	0	0	2	0	1	1	1	0	0	0	0	2	2	2	2	2	1	2	2	0	1	2	2	3	1	0	0	0	0	0	2	1
A7	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0
A8	0	0	0	0	0	0	0		2	1	0	2	1	3	0	3	0	0	0	0	0	3	2	0	0	2	1	1	3	3	3	1	0	0	0	0	0	0	1
A9	0	0	0	0	0	0	0	1		1	0	2	2	2	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	2	1	1	0	0	0	0	0	0	1
A10	1	0	0	0	0	0	0	0	0		0	3	2	2	3	1	0	0	0	0	0	0	0	0	1	3	3	3	3	2	1	2	0	0	0	0	0	2	2
A11	0	0	0	0	1	2	2	3	3	3		3	3	3	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0	2	2
A12	0	0	0	0	0	0	0	0	0	0	0		3	3	3	1	0	0	0	0	0	0	1	0	0	3	1	1	3	3	2	1	0	0	0	0	0	0	0
A13	0	0	0	0	0	0	0	0	0	0	0	2		1	1	1	0	0	0	0	1	0	0	0	3	3	0	0	2	2	1	1	0	0	0	0	0	0	1
A14	0	0	0	0	0	0	0	0	0	0	0	2	2		0	3	0	0	0	0	0	0	0	0	0	3	0	0	1	3	1	1	0	0	0	0	0	0	1
A15	0	0	0	0	0	0	0	0	0	2	0	1	0	0		0	0	0	0	0	3	1	0	0	1	0	2	3	2	0	0	2	0	0	0	0	0	3	3
A16	0	0	0	0	0	2	0	1	2	3	1	2	2	3	0		0	2	1	1	3	0	1	0	1	3	0	1	2	2	0	3	0	0	0	0	0	2	1
B1	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0		2	2	1	2	1	1	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	1
B2	0	0	0	2	2	1	0	0	0	0	0	0	0	0	2	0	2		3	3	3	2	3	1	3	0	1	1	0	0	0	1	0	0	0	0	0	2	2
B3	0	0	0	1	2	1	0	1	0	0	0	0	0	0	1	0	1	1		2	1	1	2	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0
B4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3		1	1	3	1	3	0	0	1	1	0	0	1	0	0	0	0	0	0	1
B5	0	1	1	1	2	0	0	0	0	3	0	1	1	3	3	3	2	3	3	3		3	3	1	3	3	3	3	3	2	0	3	0	0	0	0	0	3	3
B6	0	0	1	1	1	1	0	0	0	0	1	0	0	0	1	0	3	2	3	3	2		3	0	1	0	0	0	1	0	0	1	0	0	0	0	0	3	3
B7	0	0	0	2	2	0	0	0	0	0	1	0	0	0	1	0	0	1	1	1	0	0		0	1	0	0	1	0	0	0	2	0	0	0	0	0	1	0
B8	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B9	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	1	2	1	1	0		0	0	2	1	0	0	0	0	0	0	0	0	3	3
C1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		0	1	1	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1		1	0	2	0	1	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	1	2	1	1	0	3	2	2		1	3	0	0	0	0	0	0	0	1	1
C4	0	0	0	0	0	0	0	0	0	1	0	2	0	1	1	1	1	3	3	3	1	1	2	0	2	2	2	2		2	0	1	0	0	0	0	0	2	2
C5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0
C6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	1		0	0	0	0	0	0	1	0
C7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	2	0	0	0	2	0		0	0	0	0	0	1	1
C8	1	3	3	3	3	3	3	1	1	3	3	1	2	2	1	3	3	1	2	3	2	1	1	0	3	1	1	2	1	0	1	3		1	1	3	3	1	3
C9	0	0	0	0	0	1	1	2	2	2	2	3	2	2	2	2	0	0	0	0	1	0	0	0	2	3	1	0	1	3	3	2	1		1	1	1	0	1
C10	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	2	0	0	0	1	1	1	1	1	1	1	2	1	1		3	1	0	1
C11	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2	0	2	2		0	2	2
C12	0	0	0	0	0	1	0	1	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	2	1	1	2	2	0	3	0	1	1	0		0	1
D1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0		2
D2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	1	0	0	1	0	0	0	0	0	0	1	2	0	1	

Source: own elaboration

0 in the matrix) on A_2 – extraction of raw materials, while the reverse relationship between these factors, A_2 – extraction of raw materials, has a moderate influence (value of 2 in the matrix) on A_1 – selection of production technology for materials.

The determination of relationships between individual factors was carried out by the authors of the article based on the state of knowledge in the research subject, after consultations with specialists in design, construction implementation, construction managers, and experts with expertise in energy efficiency.

Following the successive steps of the DEMATEL method, appropriate calculations were performed, resulting in the determination of the following: the matrix of direct mutual influence of factors on each other A_D, the normalised matrix of direct influence A'_D, the matrix of indirect influence ΔT, and the matrix of total influence T. Subsequently, the position and relation indexes were determined using formulas (5) and (6), as well as the net flow using formula (7). The results for all phases are presented in the graph in Fig. 2.

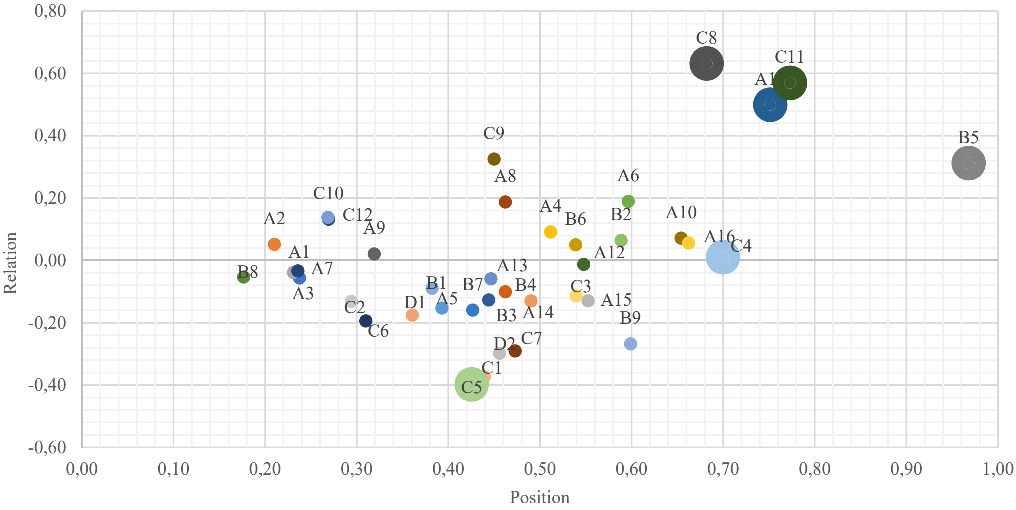


Fig. 2. Graphical interpretation of the results of the cause and effect analysis of factors affecting the reduction of the carbon footprint throughout the life cycle of a construction project.
Source: own elaboration

Due to the division into consecutive life cycle phases, an interesting phenomenon can be observed. Intuitively, one might think that the criteria belonging to the first or second phase would have the greatest influence on the other factors. However, it is clearly evident that factors belonging to Phase III (*Operational/Usage Phase*) exert a strong and causal influence. These factors are C_8 (*Regulations and legal restrictions*) and C_{11} (*implementation of a (mandatory) multi-criteria certification system for buildings*). These factors have a superior nature and require investors to comply with mandatory and significantly more restrictive requirements resulting from sustainable development principles, thereby minimising the carbon footprint in projects. Both C_8 (*Regulations and legal restrictions*) and C_{11} (*Implementation of a (mandatory) multi-criteria certification system for buildings*) were assigned to Phase III due to the consequences of possible mandatory guidelines, which are most prominent in the longest phase of the project life cycle, namely the operational phase. The factor with the strongest influence on the other factors is B_5 (*Type of materials used*), which belongs to Phase II (*Construction Phase*) of the project. Its high score results from its significant influence throughout the entire project life cycle, starting from material production (which falls under Phase I), through the costs associated with its incorporation, and extending to its usage and eventual demolition. The proper selection of construction materials can allow for their reuse in their original, unchanged form or their recycling, which should not be underestimated.

The factor with the most significant impact is C_5 (*Increasing the comfort of the facility*), which pertains to the social aspect of sustainable construction. In this regard, by adhering to actions that minimise carbon emissions, it is evident that the user comfort of the building can be significantly improved, providing occupants with a better and healthier living and working environment.

In the conducted study by the authors, they also decided to analyse the mutual interactions and determine the nature of the factors in each project phase. The aim was to verify whether the examined criteria still represent the same character and whether their strength of interaction decreases or increases when analysed solely within their respective phases. Due to the extensive nature of the analyses, it was decided to present the analysis of phase II in this article. The linkage graph for Phase II is presented below (Fig. 3).

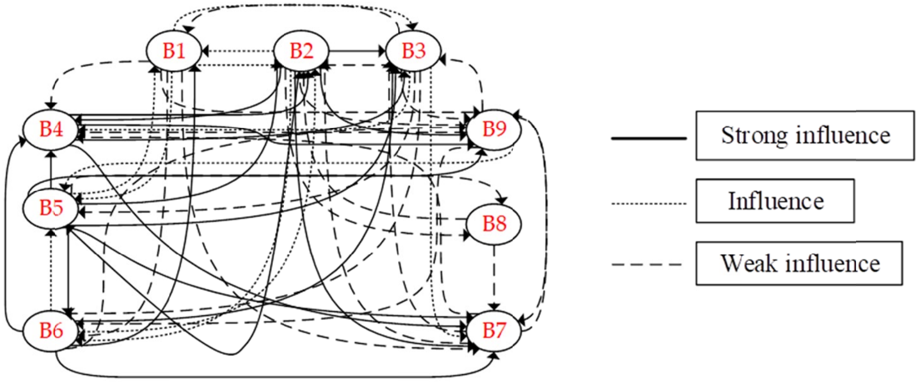


Fig. 3. Direct influence graph – expert assessment results. *Source:* own elaboration

Based on the aforementioned dependencies, a matrix of direct interactions A_D was created (highlighted in blue in TABLE 2). Subsequently, calculations were performed according to the DEMATEL method steps indicated by points (1)-(7). The values used to construct the graphical interpretation (Fig. 3) of the causal-effect analysis are presented in TABLE 3 (step 7).

Fig. 4 shows the results of the cause-and-effect analysis for Phase II (*Execution Phase / Elevation Phase / Construction Phase*).

The causal-effect analysis revealed that factor B_2 (*Technology of works (construction)*) has the greatest influence on the others, closely followed by B_5 (*Type of Materials Used*), both of which exhibit a noticeable causal character. The most significant causal effect is exhibited by criterion B_7 (*Work Efficiency: selection of work teams, size*). Overall, the causal-effect analysis of

TABLE 3

Summary of DEMATEL survey results

Nr	Name of factor	R_{T_i}	C_{T_i}	s^+	s^-	netto
B_1	transportation of construction products to/from the construction site	0,11	0,09	0,20	0,02	0,2203
B_2	technology of works (construction)	0,23	0,16	0,39	0,07	0,4639
B_3	the use of machinery	0,10	0,18	0,29	–0,08	0,2042
B_4	type of equipment used	0,18	0,16	0,33	0,02	0,3509
B_5	type of materials used	0,24	0,13	0,37	0,12	0,4860
B_6	internal construction logistics	0,19	0,10	0,30	0,09	0,3896
B_7	work efficiency (selection of work teams, size)	0,05	0,20	0,24	–0,15	0,0904
B_8	workers' travel to the site/choosing a local company	0,02	0,03	0,06	–0,01	0,0458
B_9	minimszation of construction waste	0,08	0,15	0,22	–0,07	0,1516

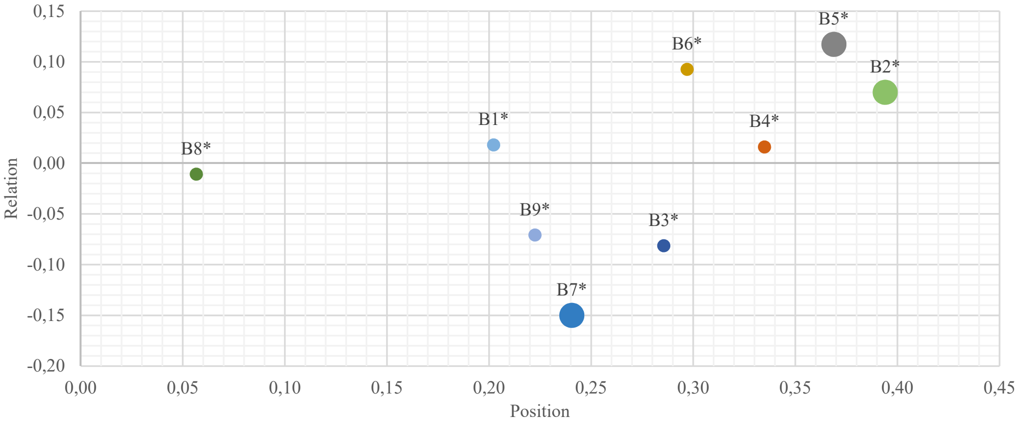


Fig. 4. Graphical interpretation of the results of the cause and effect analysis for phase II.
Source: own elaboration

Phase II indicates that approximately half of the analysed factors have a causal character, while the other half have an effect character, with some factors having values close to zero, suggesting a mixed character.

When comparing the positions of factors in the causal-effect analysis for the entire construction project life cycle and Phase II, it can be observed that the factors achieve higher values in the overall analysis due to the greater number of interconnections between factors from all phases (Fig. 5).

The situation looks different in the analysis of the values that the factors achieve in the relationship axis. In the chart presented in Fig. 5, the direction of changes resulting from the introduction of relationships between factors belonging to all phases is also shown. It is evident that, in both the Phase II analysis and the overall analysis, most factors have the same character, except for factors B_1 (*Transportation of construction products to/from the construction site*) and B_4 (*Type of Equipment Used*), which change from a causal character in the Phase II analysis

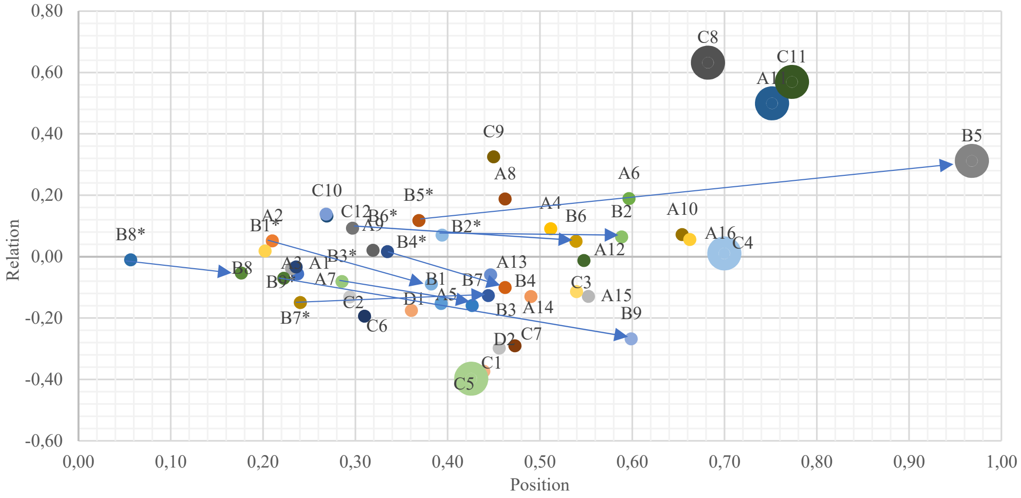


Fig. 4. Fig. 5. Graphical interpretation of the results of the cause-and-effect analysis for all phases compared to the analysis for phase II.. *Source:* own elaborotaion

to an effect character in the overall analysis. However, these factors were already located close to “0” on the scale, indicating that their character was more mixed even in the Phase II analysis. Observing the remaining factors, it is noticeable that their values mostly exhibit a decreasing trend in the analysis conducted solely for Phase II, indicating that their character becomes more effect-oriented in the overall analysis. An exception to this trend is factors B_5 (*Type of Materials Used*) and B_7 (*Work efficiency*), whose values become higher, indicating an evolution towards a stronger causal character. It is evident that the standout factor in both analyses is B_5 (*Type of Materials Used*), which has a significant influence on the other factors and exhibits a pronounced causal character.

The values of position indices (prominence) and relations were determined from the total matrix, which identifies the character of the considered factors and allows for determining their role in the process of establishing the structure of influence among objects and their influence on other objects. This enabled the determination of the degree of overall influence of factors on each other, and consequently, their comparison in terms of ranks, identifying their sometimes dual causal-effect character. The position and relation indices are presented on two-dimensional graphical charts, providing a clear form for the decision-maker (Fig. 1, Fig. 3).

5. Summary and conclusions

Due to the significant impact of the carbon footprint on activities in the construction sector, there are numerous possibilities related to this issue that can be explored. In general, the authors direct their interests towards sustainable construction, and the study of the carbon footprint is the most crucial factor concerning the environmental aspect. The article presented and analysed factors that can provide necessary knowledge for decision-making and subsequent actions related to reducing the carbon footprint associated with all construction projects. Through expert evaluation, the individual factors were assessed, and their mutual causal-effect relationships were determined. The DEMATEL method allowed for determining the character of the investigated factors. The causal-effect analysis showed that when considering the mutual influence of factors throughout the life cycle of a construction project, the factors with the greatest impact on the others are B_5 (*Type of materials used*), C_{11} (*Implementation of the mandatory multi-criteria certification system for buildings*), and A_{11} (*Application of BIM*), which belong to different phases. Interestingly, all these factors have the same directionality in the relation axis – they all have a causal character. While B_5 has the greatest impact on the others compared to C_{11} and A_{11}, it has a causal character, but its value indicating the character it assumes is significantly smaller than that of C_{11} and A_{11}.

The factor with the most causal character is C_8 (*Regulations and legal restrictions*), which also has a fairly strong influence on the other factors but does not rank in the top three. On the other hand, the factor with the most significant effect is C_5 (*Increasing the comfort of the facility*).

The relationships considered within individual phases, particularly in the presented Phase II, show a slightly different pattern. Here, the factors with the greatest impact on the other criteria of Phase II are B_2 (*Construction technology*) and B_5 (*Type of materials used*), both of which have a causal character (B_5 has the highest value on the relation axis). Meanwhile, the factor with the most significant effect in this phase is B_7 (*Work efficiency*).

Comparing the results obtained in the causal-effect analysis of Phase II to the overall analysis, it is evident that the majority of factors maintain the same character. However, in the examination of individual phases, a different factor dominates compared to the entire life cycle.

The causal-effect analysis allowed for identifying the relationships between factors that influence the reduction of the carbon footprint throughout the life cycle of a construction project, as well as in its specific phases (in this case, Phase II), and determining their character. Through this analysis, it will be easier to assess and plan the mitigation of adverse effects of construction activities and select more effective environmentally friendly solutions in planned construction projects.

Analysing individual phases can be helpful when considering a project that is already in a subsequent phase of the life cycle or when there is a real influence on reducing the carbon footprint in only a selected phase. Such analyses will enable the selection of the most effective environmental actions in line with the principles of sustainable construction.

The authors observed a certain limitation in their research, which may arise from the challenging access to information from manufacturers of specific solutions. However, various legal developments are slowly emerging that will require the presentation of the carbon footprint in production. In the future, it will be possible to obtain more accurate measures for assessing individual evaluation components, allowing for more analyses related to sustainable construction.

References

[1] ISO 14067:2018, Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification (2018).

[2] Global CCS 2021, „Global status report for buildings and construction”, (2021). https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf [Accessed: 2023-04-15]

[3] P. Wiśniewski, Ślad węglowy będą liczyć architekci. Obowiązek dla każdego budynku od 2030; Mutatorplus, (2022). https://www.muratorplus.pl/biznes/wiesci-z-rynku/slad-weglowy-co-to-aa-o8Wc-8de3-nRo7.html#obliczanie-sladu-weglowego-obowiazkowe [Accessed: 2023-04-15]

[4] PLGBC 2021, Polish Green Building Council**,** *Estimating the carbon footprint of buildings. Whole life carbon roadmap for Poland 2050,* https://plgbc.org.pl/wp-content/uploads/2022/11/estimating-the-carbon-footprint-of-buildings.pdf [Accessed: 2023-04-15]

[5] PN-EN 15978:2012, Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (2012).

[6] PN-EN 15643:2021-11, Sustainability of construction works – Framework for assessment of buildings and civil engineering works (2021).

[7] J. Steinmann, M. Röck, T. Lutzkendorf, K. Allacker, X. Le Den, Whole life carbon models for the EU27 to bring down embodied carbon emissions from new buildings: Review of existing national legislative measures. (2022). Retrieved from https://ramboll.com,

[8] ARP 2023, Agencja Rozwoju Przemysłu S.A. Oddział w Katowicach, Ślad węglowy (2023).

[9] W.K. Biswas, Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. Int. J. Sustain. Built Environ. **3**, 179-186 (2014).
DOI: https://doi.org/10.1016/j.ijsbe.2014.11.004

[10] D.Z. Li, H.X. Chen, E.C.M. Hui, J.B. Zhang, Q.M.Li, A methodology for estimating the life-cycle carbon efficiency of a residential building. Build. Environ. **59**, 448-455 (2013).
DOI: https://doi.org/10.1016/j.buildenv.2012.09.012

[11] S.S. Ramachanderan, V.K. Venkiteswaran, Y.T. Chuen, Carbon (CO_2) Footprint Reduction Analysis for Buildings through Green Rating Tools in Malaysia. Energy Procedia **105**, 3648-3655 (2017).
DOI: https://doi.org/10.1016/j.egypro.2017.03.841

[12] S.Y.C. Yim, S.T. Ng, M.U. Hossain, J.M.W. Wong, Comprehensive Evaluation of Carbon Emissions for the Development of High-Rise Residential Building. Buildings **8**, 11, 147 (2018).
DOI: https://doi.org/10.3390/buildings8110147

[13] Kyoto Protocol to the United Nations Framework Convention on Climate Change; UNITED NATIONS; 1998. https://unfccc.int/resource/docs/convkp/kpeng.pdf [Accessed: 2023-04-15]

[14] J. Zarczuk, B. Klepacki, Pojęcie, znaczenie i pomiar śladu węgloweg(carbon footprint), The term, importance and measurement of the carbon footprint. Economics and Organization of Logistics **6** (1), 85-95 (2021).
DOI: https://doi.org/10.22630/eiol.2021.6.1.8

[15] J. Śleszyński, Footprinting, czyli mierzenie śladu pozostawionego w środowisku. Optimum. Studia Ekonomiczne **1** (79), 57-67 (2016).

[16] W. Huang, F. Li, S.-H. Cui, F. Li, L. Huang, J.-Y. Lin, Carbon Footprint and Carbon Emission Reduction of Urban Buildings: A Case in Xiamen City, China. Procedia Eng. **198**, 1007-1017 (2017).
DOI: https://doi.org/10.1016/j.proeng.2017.07.146.

[17] Tažiková, Z. Struková, Reducing the carbon footprint by selecting building material. International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management. SGEM **20** (4.2), 227-234, (2020). DOI: https://doi.org/10.5593/SGEM2020V/4.2/S06.28

[18] EUR-Lex 2019, European Commission. Communication: The European Green Deal, COM (2019) 640 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640 [Accessed: 2023-04-15]

[19] EUR-Lex 2020, Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions; A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives COM/2020/662 final, https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX%3A52020DC0662 [Accessed: 2023-04-15]

[20] EUR-Lex 2022, Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions REPowerEU Plan COM/2022/230 final https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN [Accessed: 2023-04-15]

[21] R. Geryło, A. Garbacz, Zrównoważony rozwój budownictwa w świetle wyzwań klimatycznych, Materiały Budowlane **9**, 15-18 (2022).

[22] A. Wyciślok, P. Wyciślok, W kierunku budynku przyjaznego środowisku – propozycje zmniejszenia śladu węglowego w budynkach wysokościowych. Zeszyty Naukowe Wyższej Szkoły Technicznej w Katowicach **14**, 23-36 (2022).

[23] M. Fedorczak-Cisak, A. Leśniak, P. Markiewicz-Zahorski, A.P. Węglarz, Jastrzębski: Wpływ rozwiązań materiałowych przegród zewnętrznych na emisję CO2 na przykładzie budynku w standardzie nZEB. Materiały Budowlane **1**, 46-49 (2022).

[24] K. Zima, A. Przesmycka, Koncepcja zintegrowanej analizy kosztów i generowanego śladu węglowego w cyklu życia budynku. Przegląd Budowlany **92**, 10, 42-48 (2021).

[25] J. Kneifel, Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. Energy and Buildings **42**, 3, 333-340 (2010).

[26] S. Mahdi Hosseinian, M. Faghani, Assessing the effect of structural parameters and building site in achieving low carbon building materialization using a life-cycle assessment approach. Journal of Building Engineering **44**, December 202 (2021).

[27] K. Zima, Integrated analysis of costs and amount of greenhouse gases emissions during the building lifecycle. Archives of Civil Engineering **67**, 2, 413-423 (2021). DOI: https://doi.org/10.24425/ace.2021.137176

[28] P. Łasut, J. Kulczycka, Metody i programy obliczające ślad węglowy. Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN **87**, 137-147 (2014).

[29] T. Burdzik, Przestrzeń jako składnik tożsamości w świecie globalizacji. Kultura-Historia-Globalizacja **11**, 13-27 (2012).

[30] D. Wieczorek, K. Zima, Analysis of the selection of materials for road construction taking into account the carbon footprint and construction costs. Archives of Civil Engineering **68** (3), 199-219 (2022). DOI: https://doi.org/10.24425/ace.2022.141881

[31] T.C. Kuo,, The construction of a collaborative framework in support of low carbon product design. Robotics and Computer-Integrated Manufacturing **29**, 4, 174-183 (2013).

[32] Z. Karaczun, A. Kassenberg, P. Siwicki, Oszacowanie śladu węglowego rozbudowy drogi wodnej na środkowym odcinku rzeki Odry (od Brzegu Dolnego do ujścia Nysy Łużyckiej). Projekt współfinansowany ze środków Europejskiego Funduszu Społecznego w ramach Programu Operacyjnego Wiedza Edukacja Rozwój 2014-2020, Nr projektu: POWR.02.16.00-00-0070/17-00, Warszawa, marzec 2019, (2019). http://praworzeki.eko-unia.org.pl/imgturysta/files/ekspertyzy/E20.pdf, [Accessed: 2023-03-03]

[33] Z. Yeo, R. Ng, B. Song, Technique for quantification of embodied carbon footprint of construction projects using probabilistic emission factor estimators. Journal of Cleaner Production, Journal of Cleaner Production **119**, 135-151 (2016).

[34] S.H. Teh, T. Wiedmann, J. Schinabeck, S. Moore, Replacement Scenarios for Construction Materials Based on Economy-wide Hybrid LCA. Procedia Engineering **180**, 179-189 (2017).

[35] K. Ranjetha, U. Johnson Alengaram, Ahmed Mahmoud Alnahhal, S. Karthick, W.J. Wan Zurina, K.J. Rao, Towards sustainable construction through the application of low carbon footprint products. Materials Today: Proceedings **52**, 3, 873-881 (2022).

[36] L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, X. Zhang, Carbon emission of global construction sector. Renew. Sustain. Energy Rev. **81**, 1906-1916 (2018). DOI: https://doi.org/10.1016/j.rser.2017.06.001

[37] E. Heffernan, W. Pan, X. Liang, P. De Wilde, Zero carbon homes: Perceptions from the UK construction industry. Energy Policy **79**, 23-36 (2015). DOI: https://doi.org/10.1016/j.enpol.2015.01.005

[38] J. Zuo, B. Read, S. Pullen, Q. Shi, Achieving carbon neutrality in commercial building developments – Perceptions of the construction industry. Habitat Int. **36**, 278-286 (2012). DOI: https://doi.org/10.1016/j.habitatint.2011.10.010

[39] J. Li, M. Colombier, Managing carbon emissions in China through building energy efficiency. J. Environ. Manag. **90**, 2436-2447 (2009). DOI: https://doi.org/10.1016/j.jenvman.2008.12.015

[40] T. Jafary Nasab, S.M. Monavari, S.A. Jozi, H. Majedi, Assessment of carbon footprint in the construction phase of high-rise constructions in Tehran. Int. J. Environ. Sci. Technol. **17**, 3153-3164 (2020). DOI: https://doi.org/10.1007/s13762-019-02557-3

[41] S.Y.C. Yim, S.T. Ng, M.U. Hossain, J.M.W. Wong, Comprehensive Evaluation of Carbon Emissions for the Development of High-Rise Residential Building. Buildings **8**, 8, 147 (2018).
DOI: https://doi.org/10.3390/buildings8110147

[42] M. Dytczak, G. Ginda, B. Gotowała, Application potential of dematel method and its extensions for analysis of decision problems in civil engineering. Environmental Engineering 235-240 (2011).

[43] S.L. Si., X.Y. You, H.C. Liu, P. Zhang, DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications. In Mathematical Problems in Engineering **2018** (2018). Hindawi Limited. DOI: https://doi.org/10.1155/2018/3696457

[44] J.I. Shieh, H.H. Wu, K.K. Huang, A DEMATEL method in identifying key success factors of hospital service quality. Knowledge-Based Systems **23** (3), 277-282 (2010).
DOI: https://doi.org/10.1016/j.knosys.2010.01.013

[45] K. Kijewska, W. Torbacki, S. Iwan, Application of AHP and DEMATEL Methods in Choosing and Analysing the Measures for the Distribution of Goods in Szczecin Region. Sustainability **10**, 7, 1-26 (2018).

[46] Sobotka, K. Linczowski, A. Radziejowska, Substitution of Building Components in Historic Buildings. Sustainability **13**, 16, 1-13 (2021).

[47] Gabus, E. Fontela, World Problems, An invitation to Further Thought Within Framework of DEMATEL. Geneva, Switzerland (1972).

[48] T.L. Saaty, The Analytic Hierarchy Process: Decision Making in Complex Environments. Int. J. Services Sciences **1**, 1, 83-98 (2008).