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Defining Focus Areas for Digitization to Reduce Construction Industry Generated CO_2 Emissions

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Abstract. The amount of greenhouse gas emissions generated by the construction industry is significant, therefore it should be addressed to protect our environment in the 21st century. The present research is the starting point for a more complex analysis in bioengineering science. It examines the possibilities of implementing digital technologies and the gains that their application can achieve. The research provides an overview of CO_2 emissions from construction processes and identifies areas that may focus on future detailed analysis. The study consists of two main parts: a literature review and an interview with digitization experts focused on the issues identified. The present research guides future development focus areas comparing interviews by market and scientific studies. It is essential to determine how significant results can be achieved by using modern digital tools and methodologies. In this way, the extent to which they affect global emissions can be examined, and their impact can be quantified. In the research, the full spectrum of the construction industry was explored, hence we comprehensively analyzed the impact and problems of the processes belonging to each phase of the lifecycle. Although the environmental impact of raw material extraction and processing is significant, its techniques can be improved primarily through innovative solutions that require organizational or governmental intervention. By examining the building phase and post-building phases of the lifecycle, significant reductions in emissions can be achieved through more detailed design, optimized construction, and well-thought-out operation and demolition processes. As a result, immediate interventions are needed in existing methods and procedures. Sustainable construction can be supported by applying new, more accurate, innovative, and higher quality design, construction, operation, and demolition methods. These changes will facilitate the implementation of digitization processes in the construction industry at a higher level and prepare proposals for the solution of environmental problems in the construction industry.

1. Introduction

Of the greenhouse gases (GHGs) responsible for global warming, carbon dioxide (CO_2) is the most significant, accounting for about 82.9% of GHG emissions. The Environmental Protection Agency (EPA) has also confirmed that CO_2 is the primary cause of global warming among the atmosphere's various gases [1]. The use of energy and natural resources and the environmental impacts of various human activities are increasing globally. Several international studies cover the possible solutions, but the results can only be used in sub-activities. The findings also apply to the architecture, engineering, and construction (AEC) industry areas. Reducing the damage and impacts caused by construction and related works should be a priority in the 21st century. One of the possible options is the digitization by the means of Building Information Modeling (BIM), which could complement the tools offered by Life

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Cycle Assessment (LCA), creating new approaches and strategies. The purpose of the LCA methodologies is to examine and quantify the environmental impacts of assets throughout their life cycle. The process is based on ISO standards (14040, 14044). It considers raw material extraction methods, production and transportation, construction, operation, maintenance, demolition, and the recycling of building components. Examined literature separates the pre-building, building, and post-building phases and quantifies their energy requirements [2]. The pre-building phase includes the extraction of raw materials, manufacturing, packaging, and the delivery of materials to the construction site. The building phase refers to construction and installation processes, while the post-building phase can be grouped into operation, maintenance, demolition, and recycling. This research aims to identify strategies that can be improved and developed through digitization, focusing on reducing CO_2 emissions and environmental aspects.

2. Research methodology

In the research, we comprehensively examined the available literature regarding CO_2 emissions in the AEC industry. Our hypothesis was that by literature research, the focus areas could be identified where the efficiency of industrial processes can be increased and the emissions can be reduced by taking advantage of digitization opportunities. Based on the available results, we formulated a questionnaire [3]. Experts in digitization filled out this questionnaire, examining whether digital approaches of the focus areas identified are justified by market professionals. Figure 1 is intended to illustrate the three main phases and their relationship in this research.

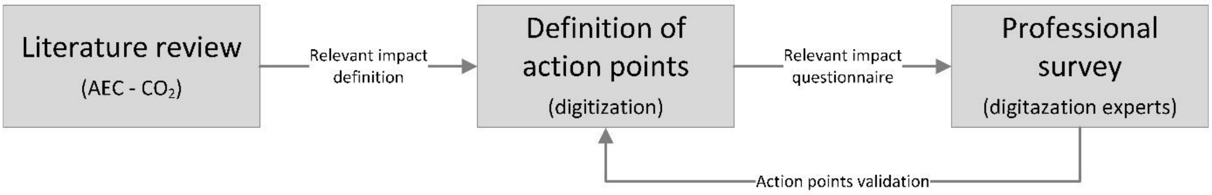

Figure 1. Research methodology concept

3. Life cycle-based environmental impact analysis

The relationship between BIM and LCA is examined in several studies [4–6], of which a comprehensive study was conducted in 2017 [7]. The study summarizes and evaluates the available options and their issues. Our research aims to examine the leading causes of CO_2 emissions and identify focus areas where digitized methodologies can support the AEC industry by developing environmentally conscious processes.

3.1. Pre-building phase

Defining the purpose of the analysis, inventory analysis, problem identification, and evaluation systems are essential aspects in calculating the environmental impact of building materials used for construction [8]. Therefore, metrics have been developed that can be employed to use environmentally conscious construction materials and architectural design processes. An example is the ECO Indicator, which supports decision-making during planning [9]. When determining GHG emissions associated with each construction material, it is necessary to consider the entire life cycle. This can be divided into three main phases: extraction of raw materials, processing, and on-site delivery. Almost 61% of global CO_2 emissions are caused by industrial activities, but the distribution of CO_2 emissions varies among the economic areas. Construction industry should be considered within this group as well but by increasing efficiency, using renewable materials, and environmentally friendly technologies [9] the environmental efforts can be supported.

3.1.1. Extraction of raw materials, mining. Mining accounts for a large amount of CO2 emissions from the AEC industry. 80% of the raw materials used by industry come from mining [10], and 30% of this is accounted for by construction works in European countries [11]. The increase in production was meant to serve the economy and the population, but this trend makes it impossible to maintain adequate living conditions in the future. In China, government regulations address the problem, reducing emissions from raw material extraction. CO2 emissions from industrial and mining activities show a deteriorating trend in China compared to the average industrial activity [12].

3.1.2. Raw material processing. In many cases, the processing of raw materials for construction use is an energy-intensive process.

Cement production is an almost inevitable part of construction works. It is the second most widely used substance on Earth after water [13]. Research has shown that its production generates the highest CO_2 emissions of all industrial processes globally. Each ton of cement produces about 700-900 kg [14–16] of CO_2, which is 5-7% of the world's total anthropogenic CO_2 emissions [17]. The emission is caused by two factors, calcination and heating for combustion. The extracted limestone is burned in furnaces heated to 1400 °C, where it decomposes into carbon dioxide (CO_2) and calcium oxide (CaO) as a result of chemical reactions [18]. Due to environmental problems, cement plants have begun to analyze and develop production technology from subsidy sources. Research can be divided into three main directions [9]: (i) Fuel and energy reduction; (ii) Carbon capture and storage; (iii) Development of new alternative materials. Table 1 shows the extent to which the available benefits are projected by the literature.

Table 1. Gains in CO_2 and energy savings can be achieved by developing the interventions examined

Examined intervention	**Process**	**Achievable profit**		**Ref.**
		Energy	**CO_2**	
Increasing energy efficiency	Transition to a dry manufacturing process	50% energy saving	~20% reduction in CO_2 emission	[19,20]
Reduction of thermal heat losses	Incinerator heating then cooling	20% energy saving	~8% reduction in CO_2 emission	[9,21,22]
Energy recovery	Electricity generation, steam or hot water production	35% energy saving	~14% reduction in GHG emission	[22–27]
Electrical energy savings	Increasing the efficiency of machines involved in the transport	7-60% energy saving	~5% reduction in CO_2 emission	[26,28]
Plant optimization	Fuel consumption, cost optimization, and pollutant emissions	3-5% energy saving	It varies depending on the technology used	[9,29,30]
Use of new pre-heaters and kilns	Development	0,6-1,1kWh/t clinker energy saving	20-90%	[9,31,32]
Maintenance	E.g.: air leak meter	46kj/kg clinker energy saving	Varies depending on the technology used	[33,34]
Pure CO_2 production and internal sequestration	Omission of the combustion process in the calciner	-	66% of all CO_2 can be stored directly	[9,25,35,36]

Lime is also a widely used raw material in the AEC industry, most used in plasters and paints. It is known as calcium oxide, which emits large amounts of CO2 during the firing process. The processing steps of fired clay bricks are as follows: excavation, sorting, shaping of treated and impregnated material, air drying, and firing [37]. Several factories have recognized biomass's potential as a more or less cleaner energy source regarding the optimization of heating, but many plants still operate by burning fossil fuels [18].

During steel production, the carbon from coal, heated limestone, and carbon dioxide from the combustion of coal used in heating, react to form carbon monoxide (CO). This CO becomes a reducing agent, creating molten iron. The process produces loads of carbon dioxide and carbon monoxide [18].

Concrete production is a complex process that requires the use of multiple raw materials and technologies. Currently, it is the most widely used material in the AEC industry, so it is necessary to address the amount of CO_2 emissions generated during its production. The relevant emission value for concrete production is 0.82 t CO_2-e/ton, including cement delivery to the concrete plant. According to the methods used in researches, it can be calculated that 290 kg of CO_2/m^3 is required for the production of 1 m^3 of 25MPa concrete, while 322 kg of CO_2/m^3 is needed for the production of 32 MPa concrete [38].

3.1.3. Transportation. According to a study made in 2012, transportation accounts for 19% of global energy consumption and 23% of energy-related CO_2 emissions [39]. However, this data comprises all types of transport, including those that cannot be linked to construction processes. According to research, construction processes account for 38% of CO_2 emissions in the US, while the industrial sector is responsible for 27%, and transportation accounts for 34% of total emissions [40]. Transportation-related work during construction processes accounts for 6% of total "light" truck traffic and 17% of medium and heavy vehicles [41]. To calculate the environmental impact of transportation processes, the "MOVES" (Motor Vehicle Emission Simulator) and "EMFAC" (Emission Factor) models have been developed [42]. With the help of refined methodologies, the amount of CO_2 emissions related to building materials transportation can be calculated. As a matter of principle, the closer the material gets to the construction site, the fewer emissions are expected. Still, the extent of CO_2 production depends on many factors, including distance, type of vehicle, type of energy used, etc. [43]. Based on a study from 2019, CO_2 emissions from construction-related transportation activities (except for concrete materials) can be calculated with an average of 0.07155 kg CO_2/ton/km [44]. In terms of concrete materials, a value of 9.4 kg CO_2/ton/km can be predicted [38]. When calculating the impact of transportation on the environment, the types of materials transported must be examined. Based on a generally accepted classification system, three main categories can be created: Made-To-Stock (MTS), Made-to-Order (MTO), and Engineered-To-Order (ETO) [45]. Further examples and calculations can be found about the relationship between vehicles and CO_2 in the research of T. Hong [46] and A.A. Nezhad [47].

3.2. Building phase

Due to the rapid development of the AEC industry, nowadays large construction projects require significant amounts of energy and, in this context, release large amounts of harmful substances into the atmosphere. Most of it is CO_2, CO, nitrogen oxides (NO), and methane (CH4) [48]. According to carbon statistics, 30% of the AEC industry's energy loss and 40% of solid waste are generated during construction [49]. Numerous studies deal with the detailed analysis of environmental impacts and GHG emissions during the building phase [50]. The study by Cole RJ [48] analyzed the on-site construction of wood, steel, and concrete structures and examined the differences between the alternatives. Comparing the results at 1m^2, concrete structural systems require the highest construction energy and lead to the highest GHG emissions (20-120 MJ/m^2 and 5-20 kg/m^2). In particular, for the production of on-site prefabricated wall segments, the required energy can be between 60-90 MJ/m^2 which is around 55–65% of the total on-site installations. In comparison, the construction energy and GHG emissions of precast concrete are much lower (20-35 MJ/m^2 and 4-5 kg/m^2). 75-80% of this is accounted for the transport of materials and equipment [48].

Factory-based prefabrication has more favorable CO_2 emissions over certain distances than on-site preparation [1]. Prefabrication improves the quality of buildings and essentially reduces waste. BIM can also help in these processes, as 3D models support the prefabrication methods [51].

Xiao-Juan Li and Yan-dan Zheng studied prefabricated piles' environmental impact in their research involving six projects [49]. According to their findings, in the construction process of precast concrete piles, CO_2 emissions are mainly caused by material transport, construction machinery, and regional energy consumption. The research shows that CO_2 emissions from construction machinery have the highest proportions (60% to 95%), followed by CO_2 emissions from material transport (0.01% to 23%). In this case, CO_2 generated on the construction site ranges from 5% to 20% [49].

Waste management is also an essential factor. Order of unnecessary materials or improper installations often leads to large amount of construction waste, highlighting the need for proper and effective strategies and enabling materials to be reused. The employment of BIM models that include material quantities can also help in optimization. In many cases, the use of outdated or unreasonably high-performance vehicles and equipment is also an issue. Efforts should be made to create optimal routes within the construction site and install equipment and machinery properly and avoid idling [52].

Research done by Andrew H. Buchanan and Brian G. Honey has compared the energy demand and CO_2 emissions of commercial, industrial, and residential buildings in New Zealand [53]. In their article, they use the energy coefficients of construction materials to estimate the total energy needed to build different structures and the resulting CO_2 emissions. The primary source of energy coefficients is a report done by Baird and Chan [54], which estimated the energy needs of all major construction materials and processes in New Zealand. The study concluded that renewable, clean energy is formulated as the global key to reduce CO_2 emissions. Buildings made from reinforced concrete and structural steel require similar amounts of energy and result in similar carbon dioxide emissions. In both cases, these values far exceed the values of wooden buildings, but they also draw attention to their problems. Wood consumption is constantly increasing. The general reaction to deforestation suggests that alternatives need to be found for the current wood uses. Unfortunately, the other options have serious drawbacks, including much higher energy requirements and significantly increased CO_2 emissions. The only solution to these problems is the global growth of sustainable planted forests. However, afforestation can also face severe problems due to finite lands [53].

Assessment criteria and cost calculating methods have already been developed, taking into account the factors affecting CO_2 emissions. Jui-Sheng Chou and Kuan-Chih Yeh have developed a process to create a CO_2 emission evaluating system and calculate environmental costs. Their simulations also considered fossil fuels, electricity, and water consumption, applied to prefabrication and on-site construction methods. Monte Carlo Simulation (MCS) was used to calculate the distribution of CO_2 emissions over the entire life cycle of prefab and monolithic construction methods. However, the estimation of CO_2 emissions is characterized by the uncertainty that it was necessary to use probabilistic factors for the analysis [1]. Estimates of the amount of GHGs and other harmful gases emitted during construction can also be assessed by a BIM model. The Athena Impact Estimator software developed and maintained by the Athena Institute offers a great alternative to this process. It can be connected to a BIM model using an SQL database [55]. Athena Impact Estimator calculates emission data for different pollutant gases (including GHG, sulfur dioxide, ozone-depleting particles, smog) for various life cycles of a building, relying on LCA principles [56].

3.3. Post-building phase

The AEC industry is responsible for 36% of global carbon emissions. 66% of this is generated during the operational phase of assets [57]. About 24% of the CO_2 emissions from the AEC industry are generated during the operation of assets. As an asset operation lasts for decades, the majority of CO_2 emissions in this phase is linked to the consumed energy, which is produced from natural gas and electricity [58]. In the case of electricity, its source can also take many different forms, thus influencing CO_2 emissions in general [55].

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Numerous studies focus on developing advanced technologies, measures, and measurement methods to reduce GHG emissions during the operational phase [59,60], but only a few studies deal with demonstrating real-time CO_2 emissions. They are based on data exchange between information collected from sensors located in an actual building and the BIM model. After the data processing, the results can be visualized by the means of the 3D model, which is a graphical projection of the critical areas. Using this method, the localized CO_2 emission data supplemented with the information of the electricity and natural gas sensors result in a dynamic BIM model. [7,61].

The LCA methodology used in construction works also defines the post-building phase, in which the effects on the environment are examined as waste energy. This includes the energy used in the demolition of the building and waste management. 70% of construction waste comes from demolition [62]. The treatment of demolition waste generates significant amounts of CO_2 through the energy related to the transport and operation of equipment [63].

The carbon dioxide associated with each structure is gradually increasing as more and more energy is used at each stage of projects to transform building materials into structural elements, individual elements into frames and modules, and then into the structure [64]. However, when a building reaches the last phase of its life, there is a risk that the invested CO_2 may be lost, as its value depends on what workflow and strategy are chosen concerning the fate of the building [47,65]. Demolition and landfilling jeopardize the value of the CO_2 invested and result in additional CO_2 emissions during further ingrained work and transportation processes to landfills [66,67].

The life cycle of building materials can be further divided into stages, starting from the demolition phase. These sections cover all activities and resources related to the processing of demolition waste, covering the period from the generation of the waste to its disposal. According to the literature, four main phases can be distinguished: demolition (waste generation phase), on-site processing, transport, and disposal [43]. These four stages can be divided into further sub-activities. By analyzing these sub-activities, the factors influencing the CO_2 emissions associated with demolition waste can be identified [68]. Several different machines are used during the demolition phase, so the CO_2 emissions from machines' operation are to be considered influencing factors. Additional devices are also needed to collect and classify the generated waste during the on-site treatment phase, so their operation can also be classified as a factor influencing emissions. As the incorporation of recycled materials can reduce the AEC industry's demand for raw materials, reusing them can reduce CO_2 emissions [69]. During the transport phase, CO_2 emissions from vehicle operation are considered as the most influential factors. During the liquidation phase, emissions depend largely on how the waste group is treated. Based on these, the CO_2 emissions during the processing of demolition waste are composed of four main factors: the operation of machinery, transport vehicles' operation, the chemical reactions in the landfill, and the reduction of CO_2 emissions from the replacement of raw materials with recycled materials.

A case study [43] shows that 45% of the total CO_2 reduction can be achieved by substituting aluminum materials. In contrast, ceramic and silicate materials can only contribute 1% to this, even though they account for 90% of demolition waste's total weight. By recycling one kilogram of aluminum, a reduction in CO_2 equivalent to 20.07 kg can be achieved, while this value is only 0.002 for ceramic and silicate materials. Therefore, it would be worth reviewing the weight and volume charging system for existing landfills, as these properties are not necessarily linked to each substance's environmental impact [43].

4. Results and discussions

Raw material extraction and processing are critical for CO_2 emissions. Process development and measurement-based design can significantly increase efficiency; however, based on our results, it is complicated to support this part of the industry with digitization. It is recommended to exploit modern process possibilities achieving energy savings and reducing CO_2 emissions.

The literature analysis and the questionnaire reveal similar results regarding the emissions of pollutants generated during construction. Recyclability analysis of planned building materials is a direction that can support the entire life cycle of assets. Besides, it is worth exploring the use of local building materials to reduce transportation's environmental impact. Waste management and waste reduction can be supported through higher quality planning processes, so BIM implementation can be considered a highly recommended solution.

The operation of assets involves significant CO_2 emissions due to the long duration. Continuous maintenance and modernization opportunities can be economically and environmentally beneficial. Figure 2 presents, that 100% of the professionals interviewed see the potential of digitization as an opportunity to reduce emissions for any assets. The predictability of functional changes, automated maintenance signals, and quantities related to more accurately calculated operation can be considered future focus areas.

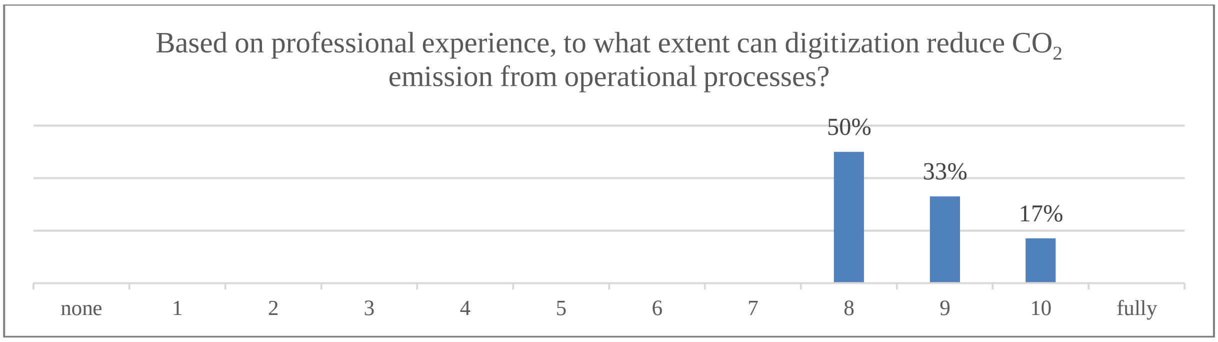

Figure 2. Summary of questionnaire replies on the operation phase

The reuse of waste generated during the demolition of assets depends on the quality and decomposability of materials and the possibilities for adaptation in the newly designed assets. If we can reuse the waste generated during demolition, we can even achieve a positive emission indicator, which indicates a reduction in the environmental load. Keeping recycling in mind requires more attention and more precise planning during the demolition phase. Still, from an ecological point of view, the extra time invested means a return on investment. The literature and the questionnaire also show similarities; therefore, it is considered a future focus area.

5. Conclusions

In summary, the optimization and modernization of processes, a higher level of thoughtfulness, planning, and applying methodologies that adapt to environmental aspects are in the interest of all of us. In many cases, reducing global warming emissions requires only process improvements and more complex design procedures. Digitization of the AEC industry supported by BIM allows for a significant efficiency increase, and by linking different databases, emissions can be calculated and further reduced.

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